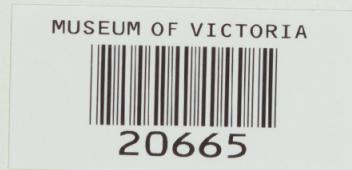


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Vol. 43

Part 1

1.—Complex Jointing on the Shield Margin near Darlington,
Western Australia.

By Michael J. Frost*

Manuscript received 16th June, 1959

Statistical investigation of the jointing in the Precambrian shield to the east of the Darling Fault shows the presence of two joint systems indicating a period of E.-W. compression followed by E.-W. tension. A possible third system and some late slickensides suggest periods of horizontal shear. Other slickensides indicate east-side-down faulting associated with the intrusion of the micro-gabbro dykes. It is suggested that these features are associated with the up-arching and collapse of an anticlinal warp prior to the more westerly collapse which produced the Darling Fault.

Introduction

The Precambrian shield of Western Australia is abruptly terminated to the west by a series of fracture lines of which the Darling Fault is the most important. Immediately east of the Darling Fault is a narrow strip of early Palaeozoic or Proterozoic sediments, and to the west geophysical work suggests the presence of between 20,000 feet and 40,000 feet of sediments (Thyer 1951) of which the top 2,000 feet are known from bores to consist of sandy shales, black shales and calcareous sandstones of Eocene and Cretaceous age. To the east the shield forms a plateau rising to an average height of about 1,000 feet above the western low-lying Swan Coastal Plain. Much of the shield is covered by laterite and is thus not available for direct study but along the margin of the plateau and in river valleys leading from the scarp excellent exposures occur and some of these have been mapped (Clarke & Williams 1926; Prider 1941; Davis 1942; Thomson 1942). From this mapping it has been possible to obtain some idea of the structure of the region and the history of the marginal faulting. One of the most recent attempts is that of Prider (1952) who says "The Darling Scarp then is an expression of a differentially eroded monoclinal structure. It was transcurrent in the late Archaeozoic, but during post-Proterozoic times there was the development of a downwarp to the west (initiated by further movement on the Darling Archaean Fault) which has been pro-

gressively sinking and being filled with sediments." He also adduces evidence that there was "a west block south and down movement in Archaeozoic times," which was continued in the late Proterozoic. Other ideas have been put forward by Jutson (1934) and Prider (1941 and 1948). It was with the belief that a statistical analysis of the complex jointing in this region could add to the knowledge of the Darling Fault that this study was undertaken.

Four quarries near Boya Siding (12 miles east-north-east of Perth) in the valley of the Helena River were chosen for study (Fig. 1). These are all in an extensive batholith the petrology, structure and extent of which have been discussed by Wilson (1958). Flow structures are not common near the quarries but where observed flow layers strike predominantly N.-S. and dip steeply to the east. Locally two varieties of granite may be distinguished, a coarse-grained porphyritic microcline granite and a fine even-grained granite of similar mineralogical composition in which the former is xenolithic. In other areas an intermediate variety is found. It seems probable that these do not represent separate granites but only repeated intrusion of deeper material into an upper partly solidified crust. Both are cut by pegmatites. The area is also crossed by numerous shear zones, many partially or completely silicified, varying in width from several feet to several chains. The majority of these have a NNE.-SSW. strike and are believed to be of earlier origin than the main jointing. Of later origin is a swarm of NNW.-SSE. striking micro-gabbro dykes. End-stage products from these have coated the earlier formed joints and the dykes themselves have caused limited alteration of the adjoining granite but the total effect has been slight.

Methods of Compilation and Study
Field Methods

In this study it was soon realised that natural exposures and shallow cuttings seldom gave data of sufficient accuracy or gave a sufficient number of joints for any but the most important

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joint systems to be evaluated. For this reason four quarries distributed as evenly as possible over the area were chosen for detailed investigation. Their location is shown on Fig. 1.

In each quarry as many joints as possible were measured. In order to avoid as far as possible subjective selection the following technique was used. In any one quarry on each level a number of points on the wall were marked and later mapped by tape and compass. These points were chosen on a horizontal plane, to within several feet, in such a way as to make the lines between any two successive points close to and approximately parallel to the nearest quarry wall. Offsets were taken from these lines to the walls, and for every joint along these lines the dip and strike were measured in the usual way. In irregular joints the strike and dip of the main surface rather than the mean was taken. Joints were not measured when there was any possibility that they had been disturbed by blasting, soil creep, etc. All planar features such as dyke walls, pegmatites, etc., were also measured. All measurements finally used were made by the author.

At the same time as the dip and strike of each joint was measured the following features were noted:

Texture—the relative roughness or smoothness of the joint face.

Planeness—the degree of approach of the joint surface to a plane, or the lack of curvature.

Veneer—the nature and thickness of the veneer on a joint.

Length—estimation of relative length.

When slickensides were present their trend and plunge were measured and recorded. In the majority of joints only a few of these features could be observed.

It is of interest, having shown the methods adopted to avoid bias, to examine the possibilities for bias that remain. The direction and vertical range of the line of traverse must have an important effect. Joints with strikes parallel to the line of traverse will obviously be biassed against in favour of those with strikes at an angle. This is a bias that has been largely ignored by previous authors. The bias for the near vertical joints has been minimized to a large extent by measuring all the joints in a quarry, thus having traverses with a number of different bearings. In those examples where this was not possible, or where the quarry was distinctly elongate, this bias must still be taken into consideration.

Flat-lying joints with strike parallel to the traverse present a more serious problem, as it is obviously impossible to traverse vertically as

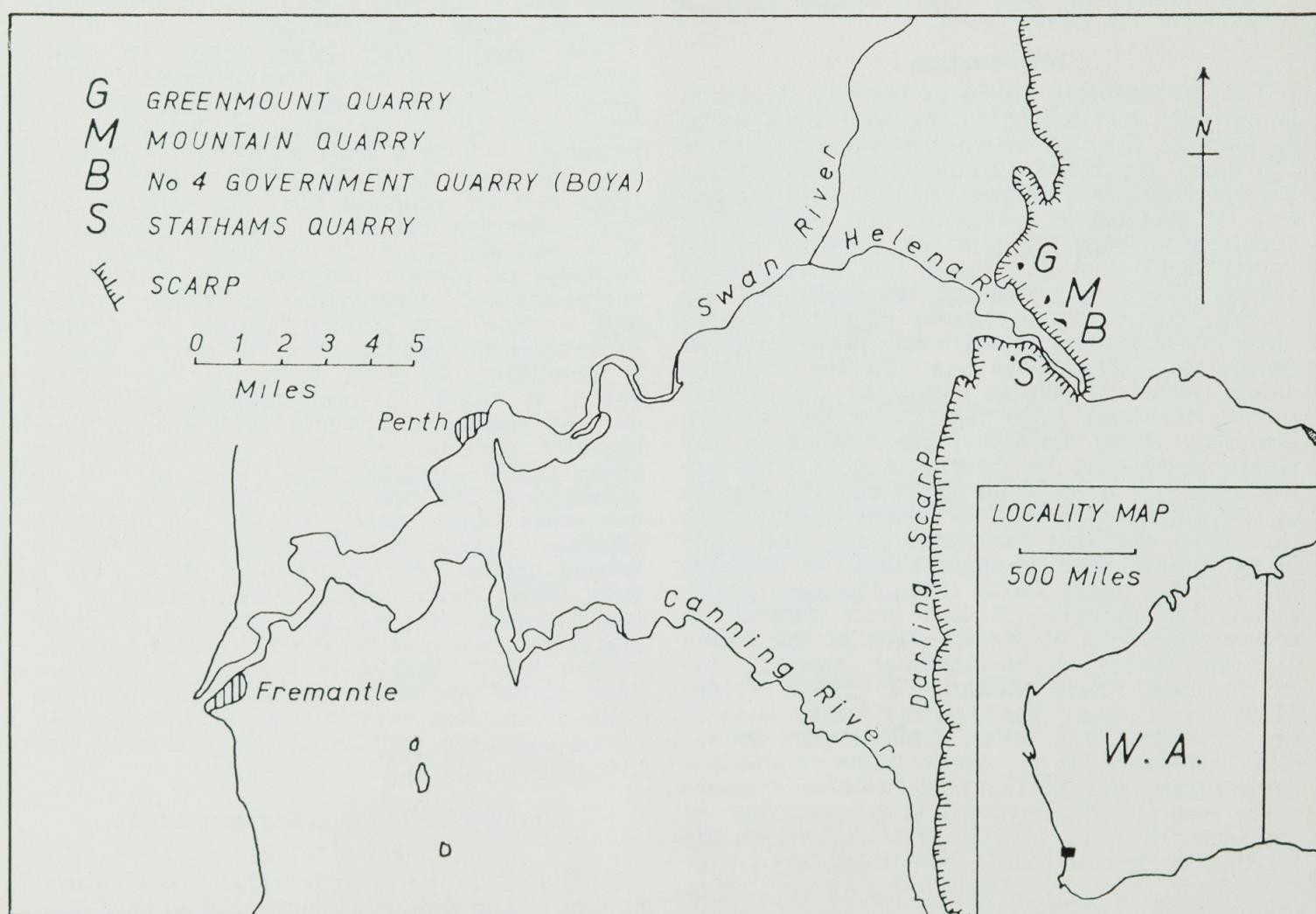


Fig. 1.—Map showing location of quarries in relation to the Darling Scarp.

far as horizontally. An effort was made to decrease the effect by specially searching for and measuring every exposed flat-lying joint. As, however, many were curving, and others difficult or impossible to reach, this probably remains a major bias. Nevertheless its structural importance must not be over-emphasised because the joints are possibly of little structural significance and may not continue to be present at depth.

Another possibility for bias, more important because it is difficult to evaluate, is that some joints may not be visible on a freshly broken surface. This may be due to welding by a solid veneer so that the rock fails to break along the joints or it may be due to preferential breakage along certain major joints. The effect of this bias was slightly diminished by attempting to follow up any traces of joints until they could be measured. Many, however, were probably missed and others could not be so followed up. Field observation tends to indicate that in this study the main effect of the bias would be to slightly flatten some of the more important maxima, as the tendency for joints not to be visible tends to be more a factor of the position of the blasting charge than of the type of joint.

Other ways in which bias may have occurred are believed to have had little significant effect in this study. It is, however, important to realise that the joint numbers obtained are proportioned not to the number of joints in the region, as might at first be expected, but to the area of the joints in the region. This is the logical result of cutting planes, which field evidence shows to be finite, by lines and counting the number of intersections. It is of considerable importance in that it means that small joints have little chance of being recorded.

Laboratory Methods

The data were next analysed in order to discover if—

- (1) there were statistically significant maxima in the joint directions;
- (2) the joints forming these maxima differed in surface characteristics;
- (3) the positions of these maxima varied significantly in different quarries.

For this purpose it was obviously necessary to plot the data in a way capable of showing their three dimensional properties. Strike and dip analysis are only applicable when some other method has shown that their use does not result in a serious loss of information.

Two methods are in use for this purpose. These are plotting the poles of joint normals on an equi-area projection (Billings 1942) or on a rectangular projection (Pineus 1951). Both were tried and it was found that the equi-area projection contoured by a method similar to that of Haff (1938) using a 1% counting circle was not only easier to interpret but had a plotting accuracy more commensurate with the accuracy with which the joint data could be obtained.

The standard error of the mean was determined for several representative groups and was found to be below 2° in each case. Modes,

rather than means, were used in later work because they could be found easily by trial and error with the counting circle.

The modes having been obtained the planes which they represent were plotted on the cyclo-graphic projection in order that their angular relations might more easily be appreciated.

In all plotting the upper hemisphere was used.

The surface features of the joints were analysed by the following method. The contour diagram was divided into a series of areas, each containing one maximum, bounded by lines of longitude and latitude. These lines were chosen in such a way as to pass through areas of minimum joint concentration. In addition a central area was chosen to include all flat-lying joints. The number of joints having definite standards of roughness, etc., was then counted in each of these groups and in one group which consisted of joints not fitting in any of the defined areas. In this way, information was obtained as to whether one maximum contained joints with surfaces or length noticeably different to those contained by any other. Due however to the large number of joints on which it was impossible to observe the surface characteristics, which may or may not bias the results, caution must be used in interpreting the results. In order to assist in visualising these data they were simplified into pairs of alternatives and the frequencies plotted on square root charts.

The slickensides were plotted by the following method. Since each slickenside must lie in the plane of the joint on which it was observed, it is just as important to know the orientation of that plane as to know the orientation of the slickenside. For this reason the poles of the joints were plotted in the normal way, then from each pole a short line was drawn parallel to the trend of the slickenside. These lines were arbitrarily drawn on the side of the point towards the primitive circle. When the direction of movement for any one slickenside was known, a small arrowhead was added pointing in the direction the outside block (i.e. assuming the joint to be tangential to the sphere) had moved. This method of representation was found to considerably simplify visualisation of the data, so much so that the loss of accuracy for slickensides on joints with steep dips was not felt to justify its rejection. When necessary, the poles of these ambiguous slickensides could also be plotted as well as their trends.

Jointing in Individual Localities

Joints in Greenmount Quarry

Greenmount Quarry is in the north-west of the area and is about one mile east of the Darling Fault. It is slightly elongate in a north-south direction. A wide vertical micro-gabbro dyke and several smaller dykes outcrop on the floor and the north wall of the quarry. Pegmatite dykes varying from $\frac{1}{2}$ in. to almost a foot wide are well exposed. Several of the smaller pegmatites are offset as much as several inches by minor movements along joint surfaces. A zone of closely spaced jointing crosses the west half of the quarry in a north-south direction. One hundred and ninety joints were measured.

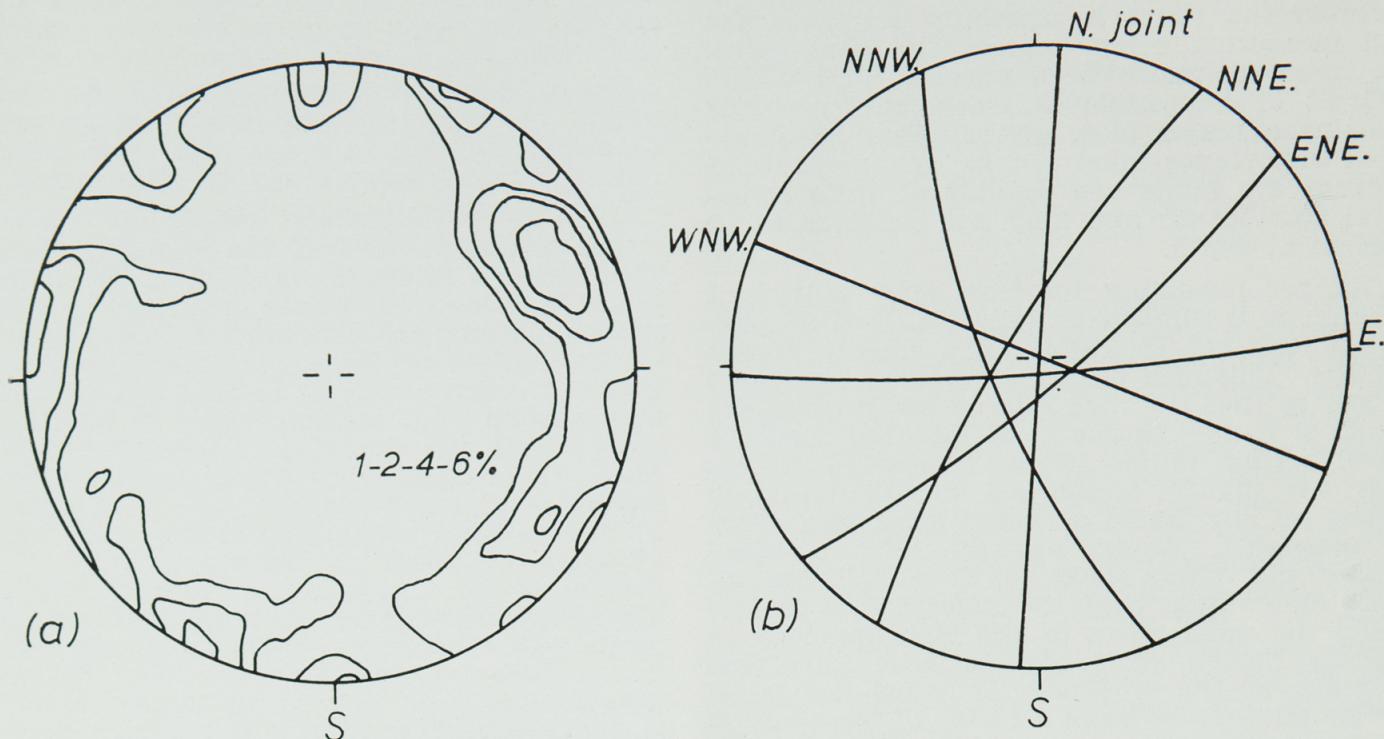


Fig. 2.—Joints in Greenmount Quarry.

(a) Equi-area contour diagrams (upper hemisphere) of 190 joint normals. (b) Cyclographic projection (upper hemisphere) of planes representing modes in Fig. 2a.

As may be seen from the contour diagram (Fig. 2a) the poles of the joints fall into six well defined groups, which are represented by modes varying in point density from 3% to 13%. When the planes represented by these modes are plotted on the cyclographic projection (Fig. 2b) a definite pattern can be recognised. Briefly the pattern may be described as an E.-W. striking plane cut in one line by two planes making acute angles to the north and south, in another by an almost N.-S. plane and in a third by two planes making acute angles to the east and west. For convenience these planes will be called after their approximate strike directions, i.e. N., NNE., WNE., etc., as shown. Where it is possible to correlate joints in other quarries with these the same terminology will be used even if the name no longer suggests the approximate strike.

The relationships between the joints are difficult to see except where erosion or blasting has exposed a clean horizontal surface. Where such occurs the most obvious feature is the tendency for the joints to cross each other with no offsetting, curving or change of strength or veneer. Another feature is that the dominant NNW. joints often terminate or are interrupted by a series of joints from several inches to over a foot long and "en echelon" in line with the original joint. These are turned clockwise about 10° with respect to the original joint. This is a typical arrangement of tension fractures and may be taken as evidence of a dextral transcurrent shearing stress having occurred in the plane of the NNW. joints. Small rough joints are occasionally found between two close NNW. joints: these are approximately vertical and approach the E. joints in strike. They may also be associated with them in origin. The E. joints are locally associated with joints that are almost vertical and approach the N. joints in

strike. These are seldom more than a foot long and may be no more than a few inches. They are sometimes found in lines along the E. joints and sometimes continue past the end of the joints. These small joints are also found distributed throughout the rock with no obvious associations. Due to their small size they probably do not produce a significant effect on the contour diagram.

The occasional pegmatites are often found to be faulted by the NNW. joints. The components of the faulting are not often determinable but the apparent displacement on a horizontal plane is always sinistral. A graphical study of the data on the surface features of the joints indicated that they fall into several groups. The E. and NNW. joints fall into what might be called the perfect group, most being long, flat and with black veneer. The NNE. joints approach this closely being mainly long with black veneer but occasionally not so smooth or flat. The flat-lying joints and possibly ENE. fall into the group with the opposite tendencies, rough, and short with many lacking veneer. In between these extremes lies a group, including the WNW., N. and possible ENE. joints. This seems to indicate that there is a definite difference in conditions of formation between the two diagonal sets and also between the N. and the E. and the flat-lying joints.

Joints in Mountain Quarry

Mountain Quarry lies towards the centre of the area and is about $1\frac{1}{2}$ miles east of the fault. Three levels are present. The quarry has a NNE. elongation and is cut by a large number of micro-gabbro dykes and pegmatites. Fifty-six joints were measured.

As may be seen from Fig. 3a there are four modes, one reaching the remarkable point density of 24.5%, and two very poorly defined

modes. When these were plotted on the cyclographic projection, it was seen that they formed a pattern strictly comparable with that of the joints at Greenmount Quarry. This not only confirms the significance of the two very poorly defined maxima, but also indicates that if every maxima is to be defined 50 joints are scarcely sufficient and where possible 100 at least should be measured.

Although the angular difference between the patterns are statistically significant the small similarity is surprising. The only differences are the absence of the N. joints which is probably not due to the small number of measurements, and the presence of a set of relatively flat-lying joints. The relative though not the absolute

heights of the maxima are also somewhat similar although the predominant development of the NNW. group is here emphasised.

Joints in No. 4 Government Quarry (Boya)

No. 4 Government Quarry (Boya) lies towards the centre of the area and is about 2 miles east of the fault. The quarry consists of a long face with a north-north-west trend, and a minor north-west face. Only one level is accessible. These features will probably bias the joint statistics as already indicated. Eighty-six joints were measured.

The quarry is cut by three relatively small micro-gabbro dykes and several pegmatites.

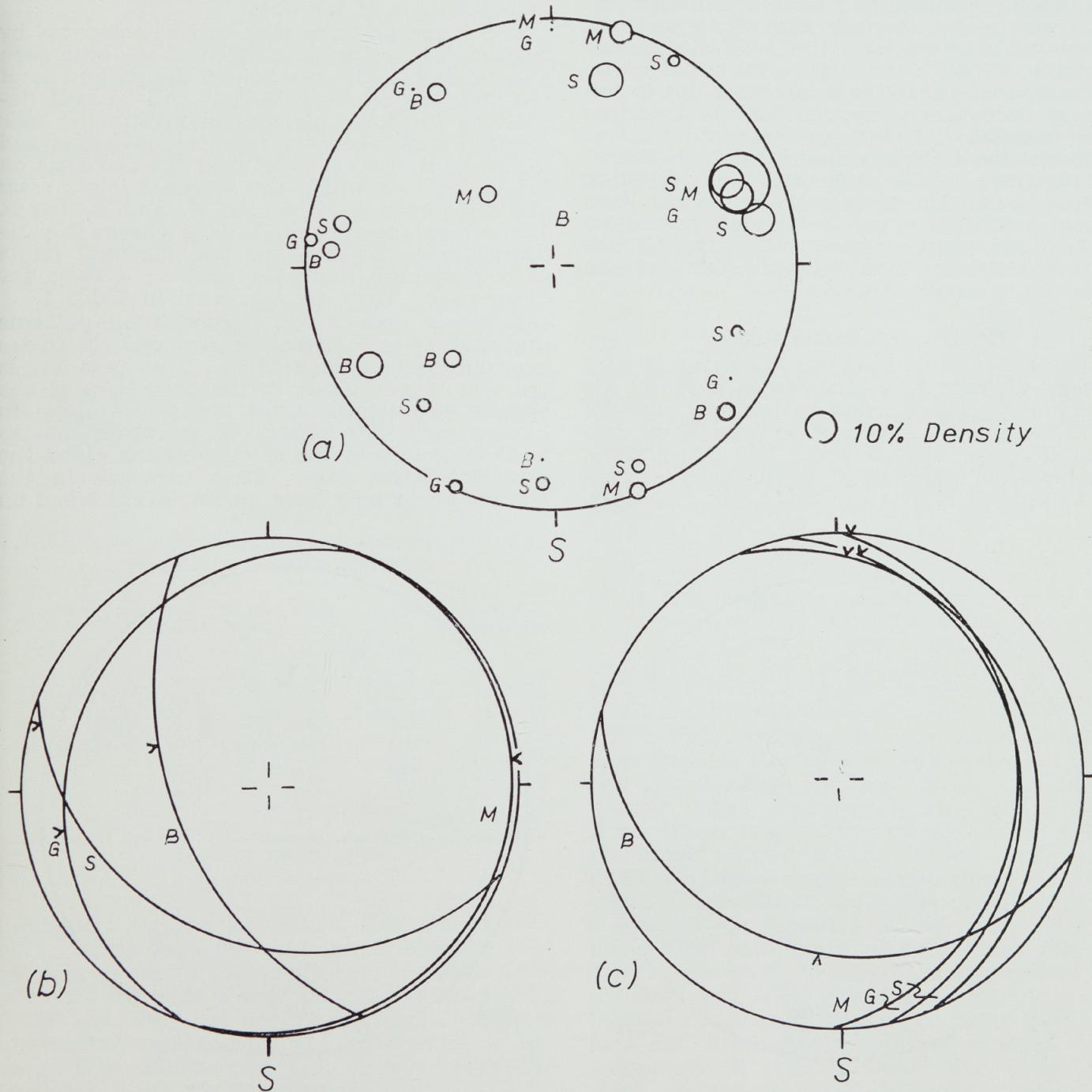


Fig. 3.—Composite diagrams (upper hemisphere). See Fig. 1 for legend.

- (a) Equi-area projection of modes of joint orientation from the four quarries (radius of circles proportional to modal densities).
- (b) Cyclographic projection of theoretical AC stress planes and B axes for ENE. and WNW. joints.
- (c) Cyclographic projection of theoretical AC stress planes and B axes for NNE. and NNW. joints.

As may be seen from Fig. 4a the joints in this quarry fall into seven groups. When plotted on the cyclographic projection it may be seen that these form the pattern with which we are already familiar and in which the flat-lying N., E., WNW., ENE., NNW. and NNE. sets can readily be identified. It may be noticed however that the angular relation and positions in space are significantly different to either pattern so far observed. That this pattern has persisted through three quarries with each pair of diagonal joints intersecting almost exactly on the plane of the E. joint is strong evidence that the standard error of the mode ($< 2^\circ$) was not underestimated. Again, the relative values of the modal densities are also roughly comparable. The NNW. is dominant, the N. is important (7%) contrasting strongly with its absence at Mountain Quarries, and the NNE. is greater than the WNW. in reverse of the usual order. Both these effects are most probably due to the bias of the quarry direction discussed earlier, it being noted that this quarry would tend to emphasise the north-trending joints while Mountain Quarries would emphasise those trending west and east. The surface characteristics were studied and were found to be similar to those of the joints at Greenmount Quarry, but not so well defined. This was probably because fewer joints were measured.

Joints in Stathams Quarry

Analysis of joint data at Stathams Quarry revealed an extremely complicated pattern. Although this pattern could be partially resolved by considering the quarry to consist of two separate parts divided along the major dyke, interpretation was still so ambiguous that it is not considered in detail in this paper. However,

the results from the east half of the quarry are quoted in the summary for completeness even though they must be accepted with extreme caution.

Comparison of Jointing in the Four Quarries

The jointing in each of the quarries can be compared from a variety of viewpoints. Among these are the angular properties of the joint pattern regardless of their orientation; the orientation and relative importance of the individual joint planes; and the orientation of the principal axes of the hypothetical stresses that may have caused the joints. Any two of these will be mutually independent and together comprehensive but a third is necessary for complete understanding of the data.

The actual patterns may best be compared by measuring corresponding dihedral angles in each and tabulating the results. If the pattern is of the Greenmount type then it will be well defined by the following measurements: the four dihedral angles between the diagonal joints and the E. joint, the angle between the two lines on the E. joint on which the diagonal joints cross and the angle between the N. and S. joints. These measurements and, as a check, the dihedral angle between the two diagonal joints of a pair were therefore used as a basis for comparison. They are tabulated in Table 1.

It will be noticed that, although the patterns are qualitatively similar, corresponding angles may differ by as much as 30° . This, it is felt, is not due to variations in the properties of the granite as other evidence has shown these to have a negligible effect. It is rather due to local variations in the stresses acting along the principal stress axes. That variation in the relative stress may have an important effect on

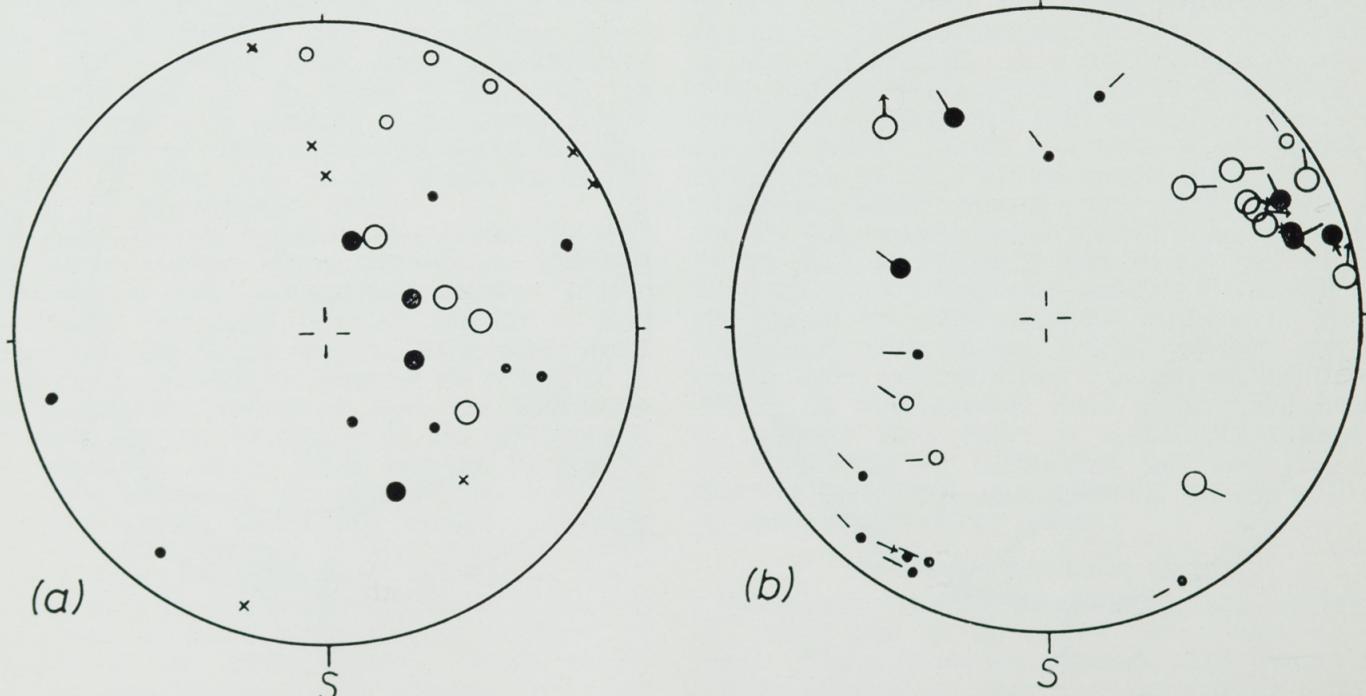


Fig. 4.—Composite equi-area projections (upper hemisphere).

(a) Pegmatite normals.

(b) Joint normals and associated slickensides. Large circles = Greenmount Quarry, large solid circles = Mountain Quarry, small circles = No. 4 Government Quarry (Boya), small solid circles = Stathams Quarry, crosses = other nearby localities.

the angle between the shear planes has been demonstrated by Parker (1942) who shows that the angle decreases when the stress acting along the axis of minimum stress becomes tensional, and by Grigg (1936) who suggests that the angle increases under high confining pressure. Another point of some interest is that in no quarry are the diagonal joints exactly bisected by the E. joint, the two angles on either side of the E. joint differing by up to 10° , and the larger angles always being associated with the same joint. This may indicate that the E. joint was controlled by a then present 'rift' direction. The average dihedral angle between the diagonal joints is close to 60° which if the joints are considered as shear planes is close to or little less than that which would be expected (Hilgenberg 1949). It is of interest to note that if the two pairs of diagonal joints were not of contemporaneous origin, as the evidence seems to indicate, and if the one set in no way offsets or deflects the other, that it might be expected that the one which was later would be the more regular in that it would be affected by fewer stresses. If the data for the two diagonal sets are examined it may be seen that the WNW.-ENE. set is the less regular in every way. This may be taken as some indication that it was the earlier to form. Other points are, the surprising difference between the ENE.-WNW. joint relations in the Mountain and Boya quarries which is not reflected in the NNE.-NNW. joint relations, which may possibly be explained as above, and the facts that the dihedral angle between the N. and E. joints is about 90° and the angle between the two lines along which the diagonal joints cross is about 30° varying from 15° to 38° .

TABLE 1

Table of dihedral angles between modal joint planes in various quarries.

| Joints | Green-mount | Mountain | Boya | Stathams | Mean Directions |
|------------------|-------------|----------|------|-------------|-----------------|
| E.-ENE. | 38 | 20 | 53 | (60 to N.) | $37 \pm 11^*$ |
| ENE.-WNW. | 64 | 37 | 95 | (116 to N.) | 65 ± 20 |
| E.-WNW. | 26 | 17 | 43 | (56 to N.) | 29 ± 10 |
| E.-NNE. | 60 | (65?) | 52 | 72 | 61 ± 7 |
| NNE.-NNW. | 128 | (134?) | 105 | 149 | 128 ± 15 |
| E.-NNW. | 68 | 68 | 53 | 77 | 66 ± 7 |
| N.-E. | 94 | ... | 86 | 95 | 92 ± 4 |
| B-B ¹ | 30 | 15 | 38 | 35 | 30 ± 7 |

B and B¹ are the hypothetical axes of intermediate strain on the E. joint.

* Average deviation.

Support for the suggestion that the WNW.-ENE. joints were there earlier is found in the jointing of one of the silicified shear zones. Here, although the rock is well jointed only the NNW., NNE. and EW. sets are represented. Although alternative explanations are possible, it is believed that silicification took place between the two periods of joint formation.

The poles of the planes forming the joint patterns of the four quarries are plotted on the equi-area projection of Fig. 3a. It is useful to remember when reading this diagram that, if we accept a standard deviation of the mean of

2° , a difference of 5° may be considered evidence and a difference of 10° may be considered proof of a significant variation. It will be noticed that significant variation takes place in the position of almost every joint. The most interesting point is the close grouping of the NNW. joint sets, the dominance and persistence of which has already been noted in the field. This seems to suggest that they were later reinforced, or possibly even reoriented by a strong and unusually constant force after their original formation. It may also be significant that the joint set with the next highest maximum is the WNW., an adjacent set.

The last method in which the joint patterns will be compared is that based upon the theoretical positions of the principal axes of the stresses which may have produced the joints. This, regardless of its theoretical implications which will be discussed later, is a very convenient way of comparing the orientations of the patterns as distinct from the planes. For this purpose it is assumed that the diagonal joints represent shear planes intersecting on the intermediate stress axis. It is also assumed that the axis of maximum stress is normal to the axis of intermediate stress and in the plane containing the axis of intermediate stress and bisecting the dihedral angle between two diagonal joints. The axis of least stress is taken as normal to this plane. As will be shown later, these assumptions are justified and probably approach the truth. The three principal axes are by construction at 90° to each other. For this reason a plane containing two of the axes and the direction of one of the contained axes is sufficient to fix the position of all the axes. For the purpose of comparison the two diagonal sets were treated separately, i.e. those with the acute angle to the north were plotted on one diagram (Fig. 3b), the others on another (Fig. 3c). Each was shown by plotting, on a cyclographic projection, the plane containing the axes of maximum and minimum normal stress and on this plane drawing a 'V' to point to the pole of the axis of maximum normal stress. This may be considered as the cyclographic projection of a simplified version of the figures used by McKinstry (1949) to illustrate stress relationships.

The close similarity, in both diagrams, of the directions for Greenmount and Mountain Quarries is noticeable. In that for N.-S. maximum normal stress Stathams is also similar while Boya differs only in the plunge of the axis of maximum normal stress. In the diagram for E.-W. maximum normal stress there is a much greater variation in the strike of this axis and a considerable variation in the positions of the planes for both Boya and Stathams Quarry. This rather tends to support the argument that the NNE. and NNW. diagonal joints are of later formation, although it must be noted that these data and those used before are to some extent correlated. It may be noted that a 40° west down rotation on a NW.-SE. axis brings all the Boya data into a position comparable with that from other quarries. It might also be noticed that a similar rotation of only 35° will serve to bring the errant data of Stathams into conformity if applied to this only.

Other Data

Plotting the pegmatites from the entire area on one diagram (Fig. 4a) brings out two points; the pegmatites are obviously not connected with the present joint system and the angular differences between the pegmatites from the Boya Quarry and from other localities are of the same direction and order of magnitude as those of the joints.

The slickensides plotted on the stereographic projection (Fig. 4b) also show an interesting feature. Although they are found on various joint sets they fall into two well-defined groups, one with approximately E.-W. trends indicating movement of the east block down, and the other with approximately N.-S. trends indicating movement of the east block to the north. These groups are even clearer when the data for the various quarries are examined separately. The relative age of the two periods of slickensiding and the validity of the first is indicated by the fact that some of the dykes show curvature of contraction joints consistent with east-block-down as the main component of movement. Since all the slickensiding is in the micro-gabbro intrusion end-stage products and is therefore post dyke-intrusion, this indicates that the east-block-down movement was the earlier.

Summary and Discussion

After the consolidation of the granite, intrusion of pegmatites, and production of the main shear zones five periods of stress are recognised. The first three resulted in the production of reinforcement of joints, the last two in the production of slickensides. Evidence has been found supporting a given sequence in these. If we accept the view based on field and laboratory evidence that the acute angle is bisected by the axis of maximum pressure, it is possible to postulate a highly probable stress orientation for most of these periods. The loadings which could have caused such stress orientation and the geological conditions which in their turn could have caused such loadings are however very numerous. Only those which seem to best fit the evidence in the limited area examined and the evidence of the general geotectonics of this part of Western Australia will be discussed.

Taking the oldest two joint systems first, they could have been produced by E.-W. compression followed by E.-W. tension. This is a common sequence either where dominant pressure is released allowing the built-up pressure at 90° to it to become dominant, as may have occurred throughout the West Australian Precambrian block, where E.-W. minor folds cross N.-S. major folds; or where the arching due to folding allows tension to develop on the crests of the major anticlines. In view of the fact that the area here is a major batholith the latter is felt to be more probable. There is some evidence that silicification of shear zones, which might be of more than one age, occurred between the formation of these two joint patterns.

This jointing seems to have been followed by another problematical joint set. The most prominent and uniform in the area, it seems to have had a late origin, yet in position and in the

field it appears simply as one set of the second joint pattern just discussed. Since it is represented only by a single set, it might tentatively be suggested that it was formed by a shearing stress possibly, in view of evidence by previous workers for similar movement, sinistral.

The interpretation of slickensides is always fraught with difficulties because there is no way of telling if they are associated with major or minor movements. Two sets of slickensides were observed, both obviously post-dyke-intrusion. No internal evidence was available to suggest their sequence. One set indicates very clearly predominantly east downward vertical movement while the other indicates sinistral shearing movement. They were necessarily formed by two separate forces. There is internal evidence that the east downward movement is the earlier and it seems reasonable to correlate this movement with the formation of the micro-gabbro dykes, both being consequent on the collapse of the up-arched structure. If this is justified then the other set may represent later return of the sinistral shearing movement. There is no record of events later than this.

Summarising it may be said that the following history seems probable. Intermittent sinistral shearing stress seems to have existed since early Precambrian. Evidence for this has been detected by Prider in the folded Archaean Jimperding Group, the Proterozoic or early Palaeozoic Cardup Group, the shear zones and the dyke formation, and by the present author in the jointing and slickensides. Superimposed on this was a major east-west compression which produced up-arching. Silicification may have occurred at this stage. The anticlinal structure later collapsed with synchronous intrusion of micro-gabbro dykes. Although these stresses may have been forerunners of those which later produced the main Darling Fault no direct connection is claimed. However recent stratigraphic and structural research has indicated that the zone of collapse may have moved toward the west with the subsequent production of the Darling and more westerly faults. If this is so it seems that the continental margin of Western Australia shows evidence of up-arching and the collapse of not only the centre of the anticlinal structure but later of the continental margin on one side of it.

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2.—New Western Australian Species of *Thysanotus* R. Br. (Liliaceae)

By N. H. Brittan*

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Eight new species of *Thysanotus* R. Br., *T. formosus*, *T. vernalis*, *T. rectantherus*, *T. pseudojuncceus*, *T. brevifolius*, *T. arenarius*, *T. spiniger*, *T. cymosus*, from the south-west of Western Australia are described and illustrated. All belong to the section of the genus characterised by the possession of six stamens.

In the course of collecting material for a study of the genus *Thysanotus* R. Br. the eight Western Australian species described in this paper have been recognised.

The specific diagnoses are in each case based on the collection rather than referring specifically to the holotype.

The districts referred to in giving details of localities are the botanical districts of Diels as published in "Die Vegetation der Erde" VII, 1906. Since there is some variation in the spelling of place names and topographical features, the usage as found in the series of 4 mile/inch Military Survey maps has been adopted as the standard.

(i) ***Thysanotus formosus* N. H. Brittan sp. nov.**
Holotype.—26 miles W. of Nannup, N. H. Brittan. 12744m-1, 26.i.1953 (PERTH)

Herba perennis, fibrae radicales fasciculatae prope basin tuberosae. *Folia* 3-4, 40 cm longa, teres, glauca, basi canaliculata membranacea dilatata, bractae radicales 2-3, membranaceae 5-8 cm longae. *Scapus* erectus 30 cm longus, umbellae 4-5, sessilae vel pedunculatae brevisimae, a specimine luxuriae umbellae in paniculam corymbosam dispositae. *Umbellae* 2-3-floris solitariae raro duo, terminalis, bractae plurae 5-7 mm longae, acuto-lanceolatae, pallide-purpurea, membranaceo. *Pedicellae* erectae 2-2.5 cm longae, infra medium articulatae. *Flores* ut in genusve, tepales exteriores 19 mm longae, linear-lanceolatae, mucronatae; tepales interiores ellipticae, fimbriatae. *Stamina* 6, antherae e filamentae atropurpurea: tria antherae exteriorae strictae, contortae, 4 mm longae, filamentis aequalae: tria antherae interiorae curvatis, contortae, 10 mm longae, filamentis duplo longioribus. *Ovarium* subglobosum: stylus strictus 10 mm longus. *Capsula* oblonga 6-7 x 4-5 mm. *Semina* 1.5 x 1.0 mm nigra arillis flavis.

Perennial, small rootstock, roots horizontal, tuberous, thickening towards base. Leaves 3-4, 40 cm long, terete, glaucous, channelled with membranous wings at the base, 2-3 short membranous bracts outside the leaves. *Scapes* simple, ca. 30 cm tall bearing 4-5 sessile to shortly stalked umbels, in luxuriant specimens the scape becomes paniculately branched. *Umbels* 2-3 flowered, solitary or rarely in twos, bracts several 5-7 mm, lanceolate with wide membranous margins, pale purple. *Pedicels* 2-2.5 cm articulate below the middle, erect in fruit. *Flowers* as in the genus, outer tepals 19 mm linear-lanceolate, mucronate; inner

tepals elliptical, fimbriate. *Stamens* 6, anthers and filaments dark purple, 3 outer anthers straight, twisted, anthers and filaments 4 mm; 3 inner anthers curved, twisted 10 mm filaments 5 mm. *Ovary* subglobose, style straight 10 mm. *Capsule* cylindrical 6-7 x 4-5 mm. *Seeds* 1.5 x 1.0 mm black with yellow aril.

Distinguished from other species by its large flowers, borne in sessile umbels most frequently in a spike and by the horizontal nature of the root system.

Type locality.—26 miles W. of Nannup.

Syntypes.—26 miles W. of Nannup, N. H. Brittan 12744m, 26.i.1953—2 sheets.

The holotype 12744m.—1 (Fig. 1 and Plate I) will be lodged at the Herbarium, Department of Agriculture, Perth; material from the other sheet will be distributed to the Herbaria at Royal Botanic Gardens, Kew and the Royal Botanic Gardens, Melbourne, for permanent retention.

(ii) ***Thysanotus vernalis* N. H. Brittan sp. nov.**

Holotype.—S. of Mt. Lesueur, N. H. Brittan 55/27, 2.x.1955 (K)

Herba perennis, fibrae radicales fasciculatae, tuberosae, glabrae. *Folia* radicalia 1-2, circa 10-25 cm longa, canaliculata, acuta, tuberculato-marginata, ad basin expansa in alata membranacea. *Scapus* 1-2, 14-35 mm longus, teres, glaber, nudus, ad dimidio superne dichotomum ramosum. *Bractae* ad nodos, acutae, 7-8 mm longae, prope basin ad 3-4 mm ad apicem. *Ramosis* ultimis 1-2 cm longis, umbellae solis desinis, bractae acutae, fuscae venosae, membranaceo-marginatae, 3 mm longae. *Umbellae* 2-5 floris, pedicellis tenuis, prope basin articulatis, 4-5 mm longis, erectis vel cernuis. *Perianthum*: tepales exteriores 10 mm longae angusto-lanceolatae, anguste membranaceo-marginatae, mucronulatae: tepales interiores ellipticae, fimbriatae. *Stamina* 6, purpurea vel flava, tria antherae exteriores 2.5-3 mm longae, rectae, contortae: tria antherae interiores 4mm longae, rectae, contortae. *Ovarium* globulum sessile, stylus erectus 3.5 mm longus.

Perennial, roots clustered, tuberous, glabrous. Radical leaves 1 or 2, 10-25 cm long, channelled, acute, tuberculate margined, expanding at the base into membranous wings. *Scapes* 1 or 2, 14-35 cm long, terete, glabrous, naked, branched dichotomously in the upper half. *Bracts* at nodes acute, 7-8 mm long at the base to 3-4 mm long at the apex. Final branches 1-2 cm long terminating in a single umbel, bracts acute, dark veined, membranous-edged, 3 mm long. *Umbels* 2-5 flowered, pedicels thin, articulated near the base, 4-5 mm long, erect to bending downwards in fruit. *Perianth* as in genus, outer tepals 10 mm long, narrow-lanceolate with narrow membranous margins, mucronulate: inner tepals elliptical, with long fimbriate margins. *Stamens* 6, purple-yellow, outer anthers 2.5-3 mm long, straight, twisted: inner anthers 4 mm

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long, straight, twisted, lower lobes cordate. *Ovary* globular, sessile, style straight, 3.5 mm long.

Distinguished from other tuberous rooted species by its open, dichotomously branched inflorescence and by the possession of straight, not curved anthers almost equal in length.

Type locality.—Region about Mt. Lesueur, S. of Irwin District, W.A. in sand plain vegetation on sandy loam or clay soils.

Syntypes: S. of Mt. Lesueur N. H. Brittan 55/27 2.x.1955 (2 sheets).

The holotype (Fig. 2) is in the Herbarium, Royal Botanic Gardens, Kew. The other sheet (Plate II) will be lodged in the Herbarium, Department of Agriculture, Perth.

(iii) ***Thysanotus rectantherus* N. H. Brittan sp. nov.**

Holotype: 15 miles S. of Kulin, N. H. Brittan 54/23-1, 6.xi.1954 (PERTH).

Herba perennis, rhizoma brevis, recta. *Radices* fibrosae haud tuberosae. *Folia* radicalia 2-3, 20-30 cm longa, plana, glabra, ad basin membranaceo marginata, 2-3 bractis membranaceis latis acutis circumdati.

Inflorescentia paniculata circa 14-17 cm longa, scapum glabrum, teres, bractae angustae, acutae, membranaceo-marginatae. *Umbellae* terminalis 1-2 florae, bractae angustae deltoidae circa 3mm longae. *Pedicellae* in florae sensim dilatatae, articulo infra medium. *Tepales* exteriores 11 mm longae angustae-lanceolatae, acutae, membranaceo-marginatae: tepales interiores ellipticae anguste fimbriatae. *Stamina* 6 aequalia, antherae 5.5-6 mm longae, atropurpureae, vix curvatae haud contortae, filamentis 2 mm longis, 0.75 mm supra basin antherae insertis, loculis basalis acutis. *Ovarium* subcylindricum, sessile, stylus 6 mm longus, rectus, apice excepto. *Capsula* maturam et semina haud video.

Perennial, short erect rootstock, fibrous roots without tubers. Leaves 2-3 radical, 20-30 cm long, flat, glabrous, expanded into membranous wings at the base, surrounded by 2-3 broad scarious bracts ending in acute points. *Inflorescence* paniculate, ca. 14-17 cm tall, scape glabrous terete, bracts narrow-acute with membranous margins. *Umbels* terminal 1-2 flowered, bracts narrow-deltoid, ca. 3 mm long. *Pedicels* expanding imperceptibly into the flower, articulated just below the middle. Outer *tepals* narrow-lanceolate, acute, with membranous margins, 11 mm long: inner *tepals* elliptical with narrow fringe. *Stamens* 6 equal, anthers 5.5-6 mm long, dark purple, slightly curved not twisted, filaments 2 mm inserted 0.75 mm from the base of the anthers, basal projections of the loculi acute. *Ovary* subcylindrical, sessile, style 6 mm long, straight, except at the apex. Ripe *capsule* and seeds not seen.

Superficially resembles some of the tuberous rooted species, e.g., *T. thyrsoideus*, but is distinguished by the leaves twice as long as the scape, by the possession of six equal and erect anthers and the very narrow fringe to the inner perianth segments.

Type locality.—S. of Kulin, Stirling District, W.A.

Syntypes.—15 miles S. of Kulin, in lateritic sand, N. H. Brittan 54/23, 6.xi.1954. (2 sheets). The holotype (Fig. 3 and Plate III) will be lodged in the Herbarium, Department of Agriculture, Perth, the other sheet is in the Herbarium, Royal Botanic Gardens, Kew.

(iv) ***Thysanotus pseudojunceus* N. H. Brittan sp. nov.**

Holotype: N. of Nannarup, W.A. N. H. Brittan 56/3-2, 5.xi.1956 (PERTH).

Herba perennis, rhizoma parva vel nulla, fibrae radicale fasciculatae, gracillimae haud tuberosae. *Folia* nulla, bractae radicales 2-3 circa 8-10 mm longae, acutae, membranaceo-marginatae, purpureae. *Caules* teres, ad basin purpureae 30-36 cm longae, plantae juvenissimae ramosae dichotomum, annosae ramosae monopodiale: *bractae* sterilae, acutae, fuscae, 4-5 mm longae, ramis horizontaliter ad basin vel erectis. *Umbellae* terminalae, pedunculatae, 2-4 florae, bractae 2-2.5 mm longae, acutae. *Pedicellae* 8-9 mm longae adscendentiae vel cernuae, articulatae prope basin. *Perianthum* ut in genere, tepales exteriores 10-12 mm longae, lanceolatae, mucronatae, anguste membranaceo-marginatae, atro-purpureus supra et infra: tepales interiores ellipticae, fimbriatae. *Stamina* 6: tria antherae exteriores 3 mm longae, luteae vel purpureae ad basin, contortae, ad latus ventras inferne squamatae: tria antherae interiores 6 mm longae, pallido-purpureae, curvatae, contortae. *Ovarium* cylindricum sessile, stylus curvatus 7 mm longus. *Capsula* cylindrica 5-6 x 3 mm periantho persistens turgido inclusa.

Perennial, little or no rootstock, roots clustered, fine, not tuberous. *Leaves* nil, 2-3 bracts at base of stems ca. 8-10 mm long, acute, membranous marginatae, purple. *Stems* terete, purple at the base green above 30-36 cm long, first branches branching dichotomously, subsequent seasons monopodially branched: barren *bracts* usually not less than 5 cm from rootstock, dark, acute, 4-5 cm long, branches horizontal then curving into erect position. *Umbels* pedunculate, terminal, 2-4 flowered, bracts 2-2.5 mm long, acute. *Pedicels* 8-9 mm long, recurved in fruit, articulated close to base. *Perianth* as in genus, outer tepals 10-12 mm lanceolate, mucronatae, with narrow membranous margins, dark purple above and below: inner tepals elliptical, fringed. *Stamens* 6: 3 outer anthers 3 mm long, yellow with purplish base, twisted, with scales on lower outer surface: 3 inner anthers 6 mm long, pale purple, twisted, curved. *Ovary* cylindrical, sessile, style curved 7 mm long. *Capsule* cylindrical 5-6 x 3 mm, enclosed in persistent turgid perianth.

The only Western Australian species with the branches horizontal at the base and then ascending. Also distinguished by the purple colour of the outer tepals in the bud stage.

Type locality.—Coastal heaths on peaty sand N. of Nannarup, W.A.

Syntypes.—N. of Nannarup, ca. 12 miles NE. of Albany, N. H. Brittan 56/3, 5.xi.1956 (6 sheets). The holotype 56/3-2 (Fig. 4 and Plate IV) will be deposited in the Herbarium, Department of Agriculture, Perth, sheet 56/3-4 is

in the Herbarium, Royal Botanic Gardens, Kew, another sheet will be deposited in the Herbarium, Royal Botanic Gardens, Melbourne. The remainder will be housed in the Herbarium, Botany Department, University of Western Australia.

Other specimens.—7 miles W. of Albany, N. H. Brittan 14/2, 14.xii.1950; 5 miles E. of Alexandra Bridge, Blackwood River, N. H. Brittan 59/11, 8.i.1959, both in Herbarium, Botany Department, University of Western Australia.

(v) *Thysanotus brevifolius* N. H. Brittan sp. nov.
Holotype.—32 miles N. of Albany, N. H. Brittan 58/32-4, 3.xi.1958 (PERTH).

Rhizoma parva, fibrae radicales haud tuberosae. *Folia* radicalia plura circa 20-25, 8 cm longa, glabra, angusta, complanata apice hebesce, bractae membranaceae latae ad apicem acutae circumdatae. *Scapum* 18-24 cm longum, teres, glabrum, bracta sterilis una circa 4 cm apicem inferne infrequentibus. *Inflorescentia* multiflora, circa 20-50 floris. *Umbella* una, bractae circa 5 mm longae, late cuneatae, exteriore virides, anguste membranaceo-marginatae; interiores plerumque membranaceae. *Pedicellae* circa 8-10 mm longae. *Perianthum*: tepales exteriore 6-7 mm longae, 2 mm latae, late membranaceo-marginatae, tepales interiores ellipticae, fimbriatae. *Stamina* 6: tria antherae exteriore 2.5 mm longae, tria interiores 4 mm longae, loculis ad basin eminentibus, apice semicircularis. *Ovarium* cylindricum, stylus rectus, ad apicem anguste obconicus brevibus trilobatus. *Capsula* maturam et semina haud video.

Plant with small rootstock with fibrous roots. Radical leaves several, ca. 20-25, up to ca. 8 cm long, glabrous, narrow, flat with blunt apex, surrounded by broad membranous bracts with acute apices. Scape terete, glabrous, 18-24 cm tall, rarely with single sterile bract some 4 cm below the apex. Inflorescence many flowered, ca. 20-50 flowered, umbel one, bracts broadly cuneate ca. 5 mm long, outer ones green with narrow membranous margins, inner ones largely membranous. Pedicels ca. 8-10 mm long. Perianth: outer tepals 6-7 mm long, ca. 2 mm broad with broad membranous margins; inner tepals elliptical, fringed. Stamens 6: outer three 2.5 mm long, inner three 4 mm long, with short projecting lobes at the base, rounded apex. Ovary cylindrical, style straight, narrow obconic at the apex, shortly trilobate. Ripe capsule and seed not seen.

Differs from *T. glaucus* in its single multi-flowered umbel, flowers with six stamens and the possession of some tuberous roots.

Type locality.—South Stirling sand plain, Stirling District.

Syntypes.—South Stirling sand plain, 32 miles N. of Albany, N. H. Brittan 58/32, 3.xi.1958 (6 sheets). The holotype 58/32-4 (Fig. 5, nos. 3 and 4) will be deposited in the Herbarium, Department of Agriculture, Perth, sheet 58/32-2 (Plate V) will be deposited in the Herbarium, Royal Botanic Gardens, Kew, sheet 58/32-3 will be deposited in the Herbarium, Royal Botanic Gardens, Melbourne. The remainder will be housed in the Botany Department, University of W.A.

Other specimens.—Moist valleys, Stirling R. F. Mueller s.d. (Fig. 5, No. 1). Source of Blackwood River, Cronin s.n. 1889 (Fig. 5, No. 2) (MEL).

(vi) *Thysanotus arenarius* N H. Brittan sp. nov.
Holotype.—Cape Naturaliste, N. H. Brittan 20/5, 20.xii.1950 (PERTH).

Herba perennis, rhizoma brevissime, fibrae radicales paucae, crassae, haud tuberosae. *Folia* radicalia tempore florationis praesentia (viridis), 23 cm longa, plana, paucis ciliis marginata. *Caulis* 50-70 cm longae aut longiores, rigidae, teres, striatae, ad basin hirsutae cum pilis brevibus patentibus vel glabrae superne raro totum glabrae: ramosae monopodiales, ramulis strictis, adscendentibus. *Umbellae* terminales, 2- raro 3- florae. *Bractae* membranaceae, acuminatae 3 mm longae. *Pedicellae* circa 10 mm longae, prope basin articulatae, erectae vel cernuae. *Flores* ut in genere: tepales exteriore circa 15 mm longae, anguste linearae, 2 mm latae, mucronatae; tepales interiores ellipticae, fimbriatae. *Stamina* 6, declinata: tria antherae exteriore 5.5 mm longae, strictae, parum curvatae; tria antherae interiores 9 mm longae, curvatae, contortae. *Ovarium* subglobosum, sessile, stylus 11 mm longus, curvatus, declinatus. *Capsula* cylindrica 5 mm longa, perianthum laxo adhaerens inferne. *Caulis* ad nodos inferiores radicosae.

Perennial, short rootstock, roots few, thick, not tuberous. Leaves present at time of flowering, up to 23 cm long, flat, sparsely ciliate margined. Stems 50-70 cm or longer, stiff, terete, striate, ridges hirsute towards the base with short patent hairs, tending to be glabrous above, occasionally whole plant glabrous; branching monopodially, branches simple ascending. Umbels terminal, usually 2 occasionally 3 flowered. Bracts acuminate, membranous, 3 mm long. Pedicels ca. 10 mm long, articulated near the base, recurved in fruit. Flowers as in the genus: outer tepals ca. 15 mm long, narrow-linear, 2 mm wide, mucronate; inner tepals elliptical, fimbriate. Stamens 6, declinata: 3 outer anthers 5.5 mm long, straight to slightly curved; 3 inner anthers 9 mm long, curved and twisted. Ovary subglobose, sessile, style 11 mm long, curved, declinate. Capsule cylindrical, 5 mm long, the persistent perianth remaining adherent above, splitting round the capsule. Stems tending to root at nodes.

Differs from *T. dichotomus* in the monopodial branching, hirsute ridged stems and lack of large rhizome. It is the only W.A. species which shows the tendency to produce vegetative buds in the lower axils of the stems.

Type locality.—Geographe Bay, N. Warren district, on coastal sand with *Agonis flexuosa*.

Syntypes.—Cape Naturaliste, N. H. Brittan 20/5, 20.xii.1950 (Fig. 6, No. 1, and Plate VI) will be deposited in the Herbarium, Department of Agriculture, Perth: Busselton, N. H. Brittan 20/1, 20.xii.1950 is in the Herbarium, Royal Botanic Gardens, Kew: 4 miles S. of Mandurah, N. H. Brittan 55/36, 5.xii.1955 (Fig. 6, Nos. 2 and 3) will be deposited in the Herbarium, Royal Botanic Gardens, Melbourne.

Other Specimens.—Mt. Eliza, Perth, W.A.: L. Preiss, 1564, 2.x.1839 (CP, LD, LE., MEL, S)—all these specimens have been incorrectly attributed to *T. anceps* Lindl. (Lehmann, Plantae Preissiana, ii.37 1846): Shark Bay to Murchison River, F. Mueller s.n. Oct. 1877: Greenough River, F. Mueller s.n. Nov. 1877 (MEL): Claremont, W.A. Andrews, 999, 29.xii.1901 (BM): North of Muchea, N. H. Brittan 52/65, 30.xi.1952: Salt River, N. H. Brittan 58/30, 2.xi.1958: N. of Scott River, N. H. Brittan 59/6, 7.i.1959 in Herbarium, Botany Department, University of W.A.

(vii) ***Thysanotus spiniger* N. H. Brittan sp. nov.**
Holotype: Hill River, N. H. Brittan 52/39, 24.ix.1952 (vegetative) and Botany Department experimental garden, N. H. Brittan 58/39, 8.xi.1958 (flowers) (PERTH).

Herba perennis, rhizoma crassa brevis, fibrae radicales fasciculatae, elongatae, haud tuberosae. *Folia* plura ante florationis marcescentia, circa 15 cm longa, complanata, marginis et dorsum brevis hirsutibus. *Caules* vel 40 cm longae, rigidae, teres, nuda, sulcatae, pilis brevibus paulum recurvatis hirsutibus; copiose ramosus, ramis brevibus dichotomose ramosus, ramulis ultimis in aculeis brevibus terminibus. *Bractae* inferne folioides, ciliato-marginatae, bractae superne breves, acutae. *Umbellae* 1-2 florae, bractae breves deltoides. *Perianthum*: tepales exteriore late linear-lanceolatae, mucronatae, anguste membranaceo-marginatae, circa 13 mm longae, 3 mm latae; tepales interiores ellipticae, fimbriatae. *Stamina* 6, antherae aequales, 8 mm longae, rectae haud contortae, stylus adversus declinatus. *Ovarium* subglobosum, stylus curvatus. *Capsulam* maturam et semina haud video.

Perennial, short thick rhizome, roots clustered, long not tuberous. Leaves flattened, several per shoot at the start of the growing season, up to 15 cm long, shortly hirsute on margins and on ridges on the back, dying before flowering period. Shoots stiff, up to 40 cm tall, naked, terete, ridged, with short, somewhat recurved hairs on the ridges; copiously branched, side branches short and branched again dichotomously, final branches terminating in a short prickle-like cone. Lower bracts leaf-like, ciliate margined, upper ones short, acute. Umbels 1-2 flowered, bracts short, deltoid. Perianth: outer tepals broadly linear-lanceolate mucronate, with narrow membranous margins, ca. 13 mm long, 3 mm wide; inner tepals elliptical, fimbriate. Stamens 6, equal, anthers 8 mm long, straight not twisted, de-clinate opposite to the style. Ovary subglobose, style curved. Ripe capsule and seed not seen.

Differs from *T. dichotomus* in its more rigid habit, the semi-pungent ends of the branches not bearing flowers and the six, straight equal length anthers.

Type locality.—Hill River area, N.W. Avon District.

Holotype.—Hill River, N. H. Brittan 52/39, 24.ix.1952, flowers from plant cultivated in experimental garden of Botany Department, University of W.A., N. H. Brittan 58/39, 18.xi.1958 (Fig. 7, Nos. 2, 3, and 4 and Plate VII) will

be deposited in the Herbarium, Department of Agriculture, Perth.

Other specimen.—Nr. Mogumber, N. H. Brittan 55/13, 24.ix.1955 in Herbarium, Botany Department, University of W.A.

(viii) ***Thysanotus cymosus* N. H. Brittan sp. nov.**
Holotype.—30 miles S. of Kulin, N. H. Brittan 58/22-1, 27.x.1958 (PERTH).

Herba perennis? *Fibrae* radicales fasciculatae, tuberae ad 5-7 cm ab caule productae. *Caulis* vaginis foliis vetustis circumdatis. *Folia* 2-3, teres, glaber, 20-30 cm longa. *Scapum* haud ramosum ad 20-25 cm, inflorescentia cymosa superne ferens. *Umbellae* terminales, bractis circa 4 mm longis, deltoideis, latis membranaceo-marginatis circumdatis. *Umbellae* 4-6 florae, pedicellis 10 mm longis, erectis vel cernuis. *Perianthum*: tepales exteriore 9-10 mm longae, linearae, 1.5 mm latae, 5-venosae, breviter mucronatae; tepales interiores 8-9 mm longae, ellipticae, fimbriatae. *Stamina* 6, antherae inaequales, rectae haud contortae: tria interiorae 4.5 mm longae; tria exteriorae 3 mm longae; filamentae 1.5 mm longae. *Ovarium* sessile, globosum-subcylindricum. *Stylus* strictus 4 mm longus. *Capsulam* maturam haud video.

Perennial herb? Roots fibrous with few elliptical tubers some 5-7 cm from the stock. Stock surrounded by leaf sheaths of old leaves. Leaves 2-3, terete, glabrous, 20-30 cm long. Scape simple to 20-25 cm, bearing a cymose inflorescence. Umbels terminal, enclosed within deltoid bracts ca. 4 mm long with wide membranous margins. Umbels 4-6 flowered, pedicels 10 mm long, becoming reflexed in fruit. Outer perianth 9-10 mm long, linear, 1.5 mm. wide, terminating in a short mucrone, 5-veined; inner perianth 8-9 mm long, central part elliptical with fringe some 4 mm wide. Stamens 6, anthers unequal, straight not twisted; three outer 3 mm long, three inner 4.5 mm long, filaments 1.5 mm long. Ovary sessile, spherical-subcylindrical. Style straight, 4 mm long. Ripe capsule not seen.

Its affinities appear to be with *T. scaber* from which it can be distinguished by the glabrous leaves and the open cymose inflorescence.

Type locality.—Sand plain between Kulin and Lake Grace, W.A.

Syntypes.—30 miles S. of Kulin in sand plain heath vegetation, N. H. Brittan 58/22, 27.x.1958 (2 sheets). The holotype 58/22-1 (Fig 8 and Plate VIII) will be deposited in the Herbarium, Department of Agriculture, Perth and 58/22-2 will be deposited in the Herbarium, Royal Botanic Gardens, Kew.

Other specimen.—Ongerup-Borden in low heath vegetation, N. H. Brittan 58/23, 28.x.1958 in Herbarium, Botany Department, University of W.A.

Acknowledgments

The author wishes to express his gratitude to Dr. R. Melville of the Herbarium, Royal Botanic Gardens, Kew, with whom he had helpful discussions while working at Kew in 1957, and to Mr. P. R. C. Weaver of the University of Western Australia for assistance with the Latin diagnoses.

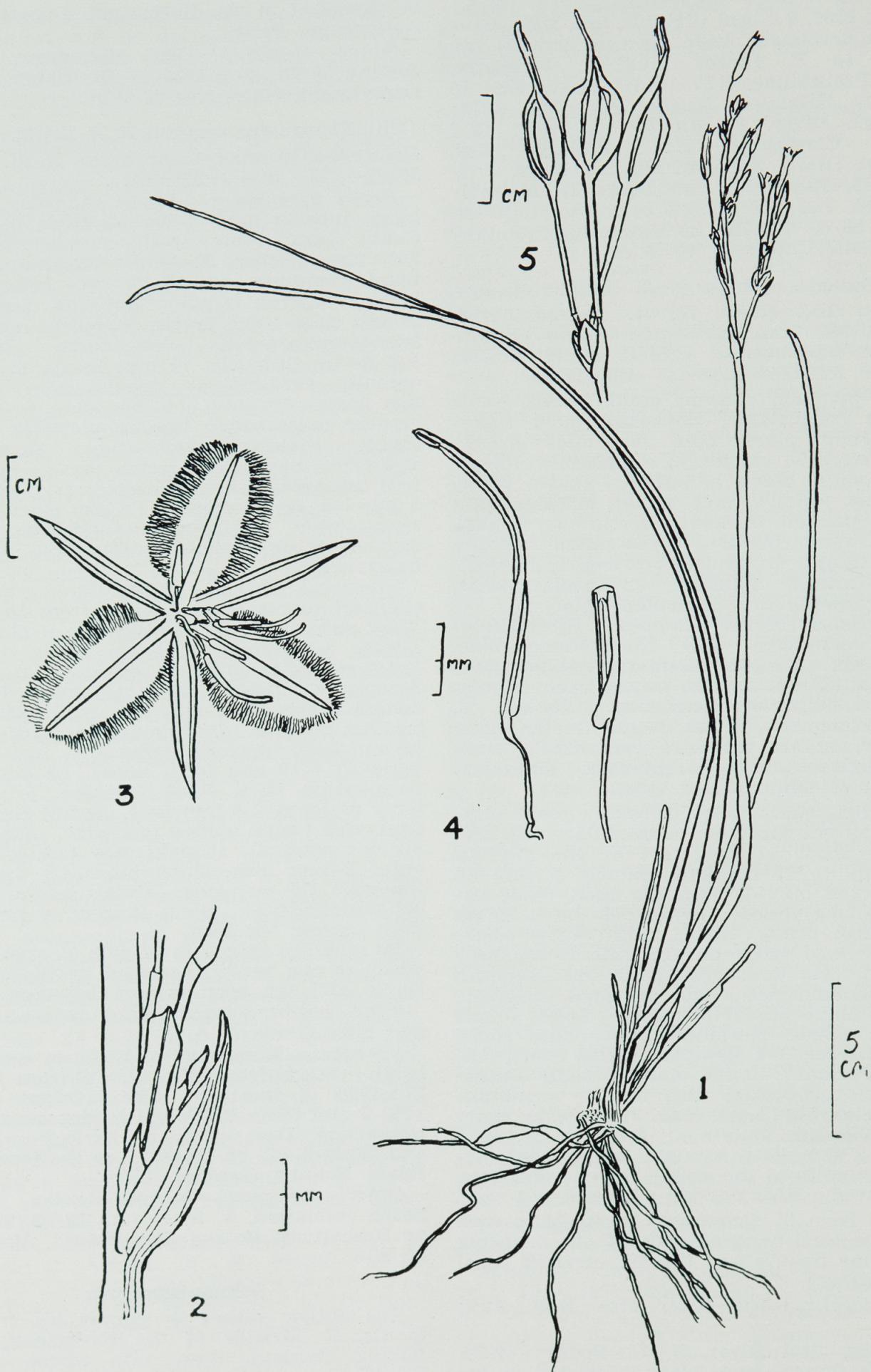


Fig. 1.—*Thysanotus formosus* N. H. Brittan.

1.—Whole plant. 2.—Detail of sessile umbel. 3.—Flower. 4.—Detail of stamens. 5.—Umbel with capsules. 1-4 inclusive from holotype. 5.—from collection (locality unspecified) Wellstead 1900 (K).



PLATE I.

Thysanotus formosus N. H. Brittan holotype.

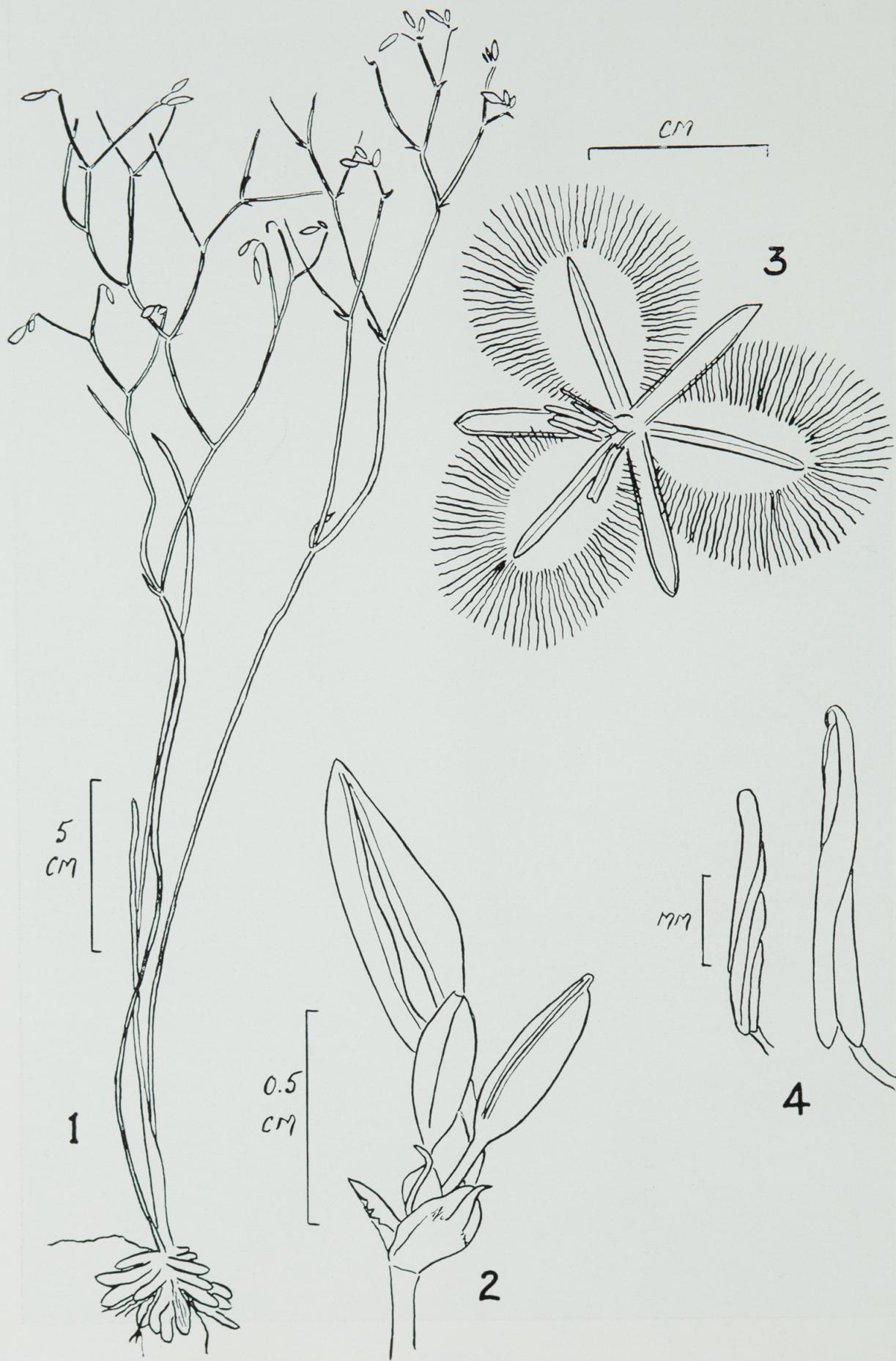


Fig. 2.—*Thysanotus vernalis* N. H. Brittan holotype.

1.—Whole plant. 2.—Detail of umbel. 3.—Flower. 4.—Detail of stamens.

No. 5480

Fig. 6



THE UNIVERSITY OF WESTERN AUSTRALIA

Name *Thysanotus vernalis* sp. nov.

Loc. S. of Mt. Newman.

Hab. On a flat area, S. of Mt. Newman.

Notes Dry sandy soil.

Coll. A. G. Smith No. 5480

PLATE II.

Thysanotus vernalis N. H. Brittan syntype.

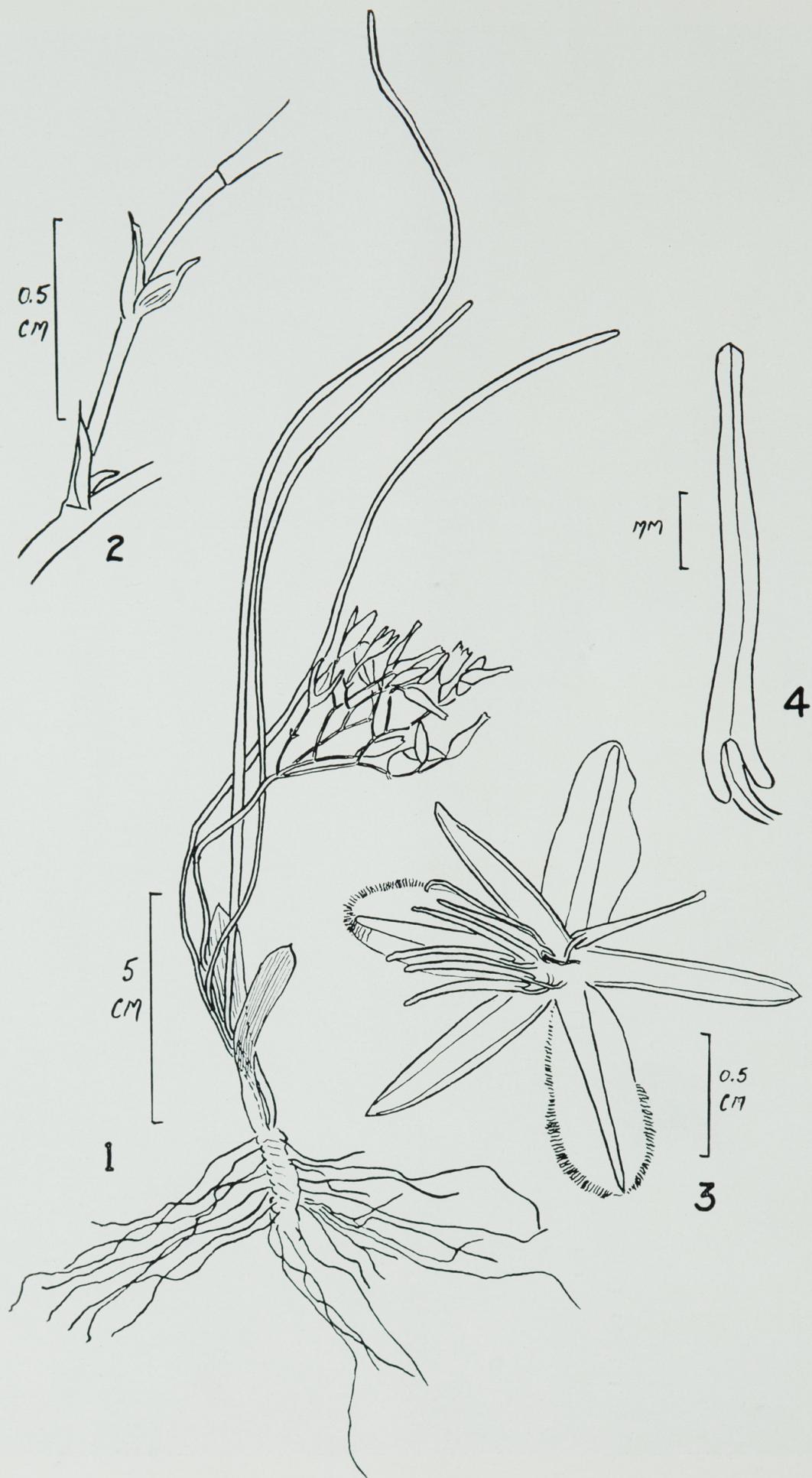


Fig. 3.—*Thysanotus rectantherus* N. H. Brittan holotype.

1.—Whole plant. 2.—Portion of inflorescence. 3.—Flower. 4.—Detail of stamen.



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Name: *Thysanotus rectantherus* N. H. Brittan
Locality: Karratha, Western Australia
Habitat: Grassy open ground
Notes: Flowers yellowish-green, petals deeply lobed.

PLATE III.

Thysanotus rectantherus N. H. Brittan holotype.

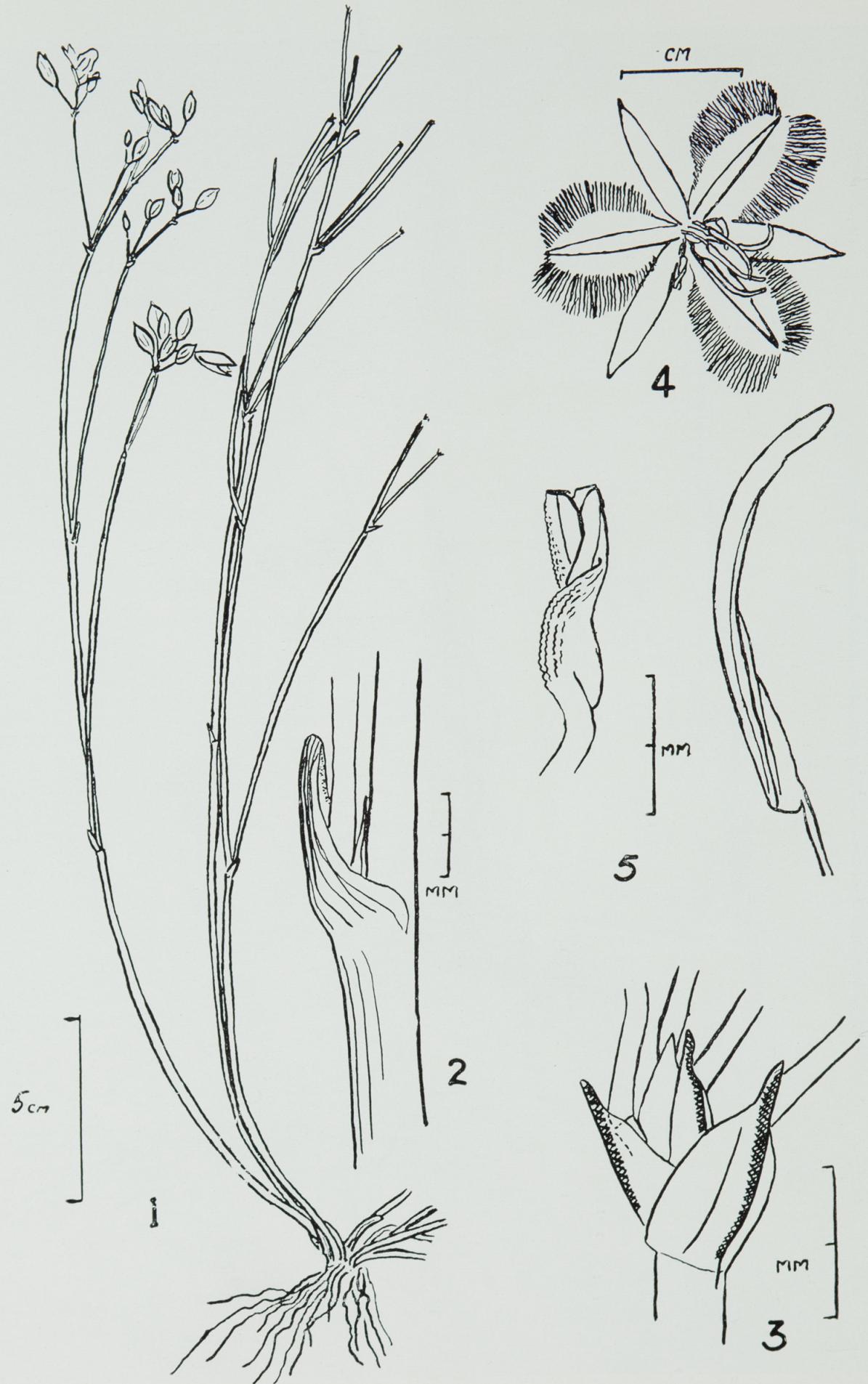


Fig. 4.—*Thysanotus pseudojuncus* N. H. Brittan holotype.

1.—Part of whole plant. 2.—Detail of stem node. 3.—Detail of umbel. 4.—Flower. 5.—Detail of stamens.



PLATE IV.

Thysanotus pseudojuncus N. H. Brittan holotype.

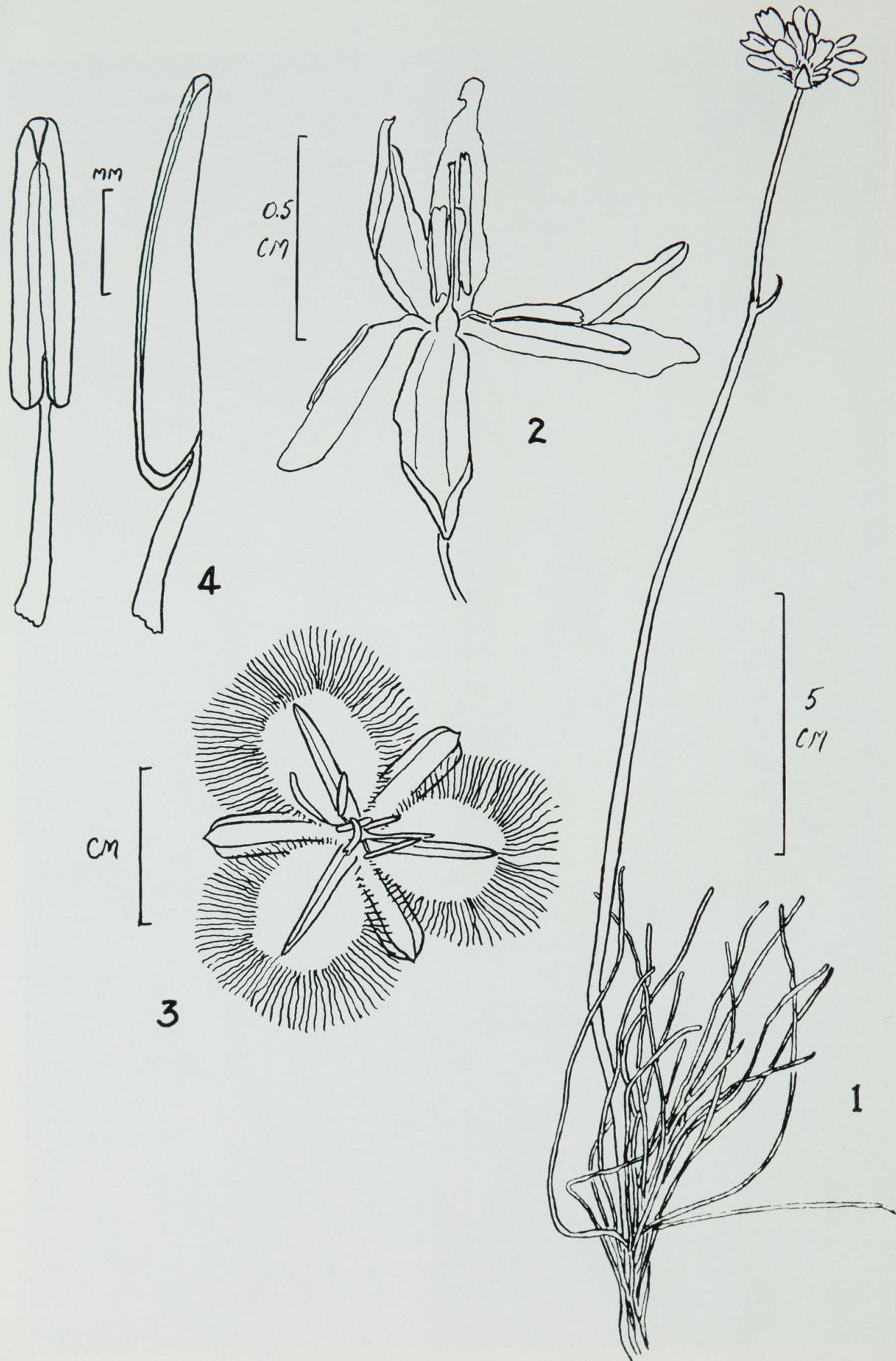


Fig. 5.—*Thysanotus brevifolius* N. H. Brittan.

1.—Whole plant from collection "Moist valleys, Stirling R." F. Mueller (MEL). 2.—Flower from collection "Source of Blackwood River" Cronin (MEL). 3.—Flower from N. H. Brittan 58/32-4 holotype. 4.—Detail of stamens from N. H. Brittan 58/32-4 holotype.



PLATE V.

Thysanotus brevifolius N. H. Brittan syntype.



Fig. 6.—*Thysanotus arenarius* N. H. Brittan.

1.—Whole plant from N. H. Brittan 20/5 holotype. 2.—Flower from N. H. Brittan 55/36 syntype. 3.—Detail of stamens from N. H. Brittan 55/36 syntype.

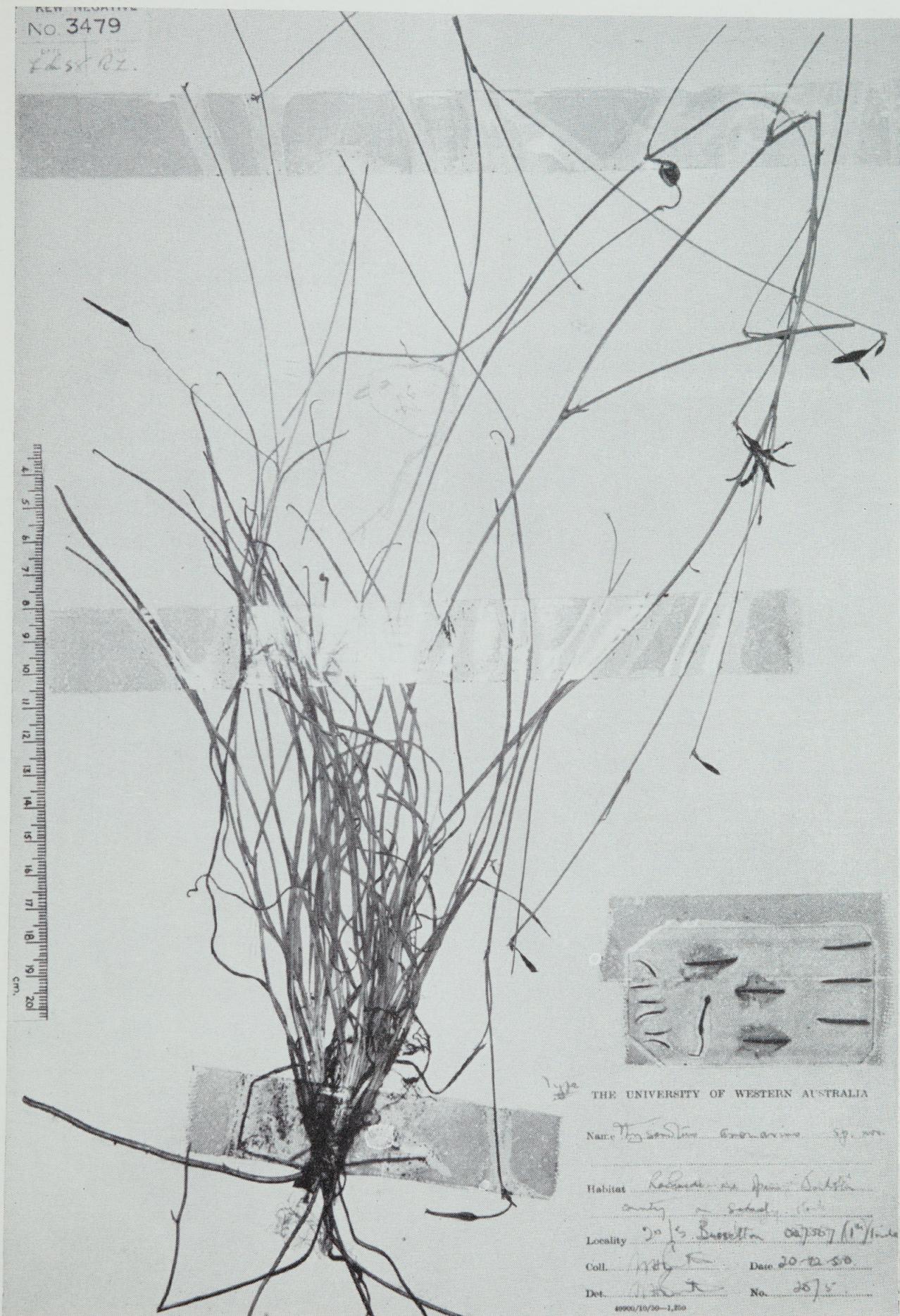


PLATE VI

Thysanotus arenarius N. H. Brittan holotype.

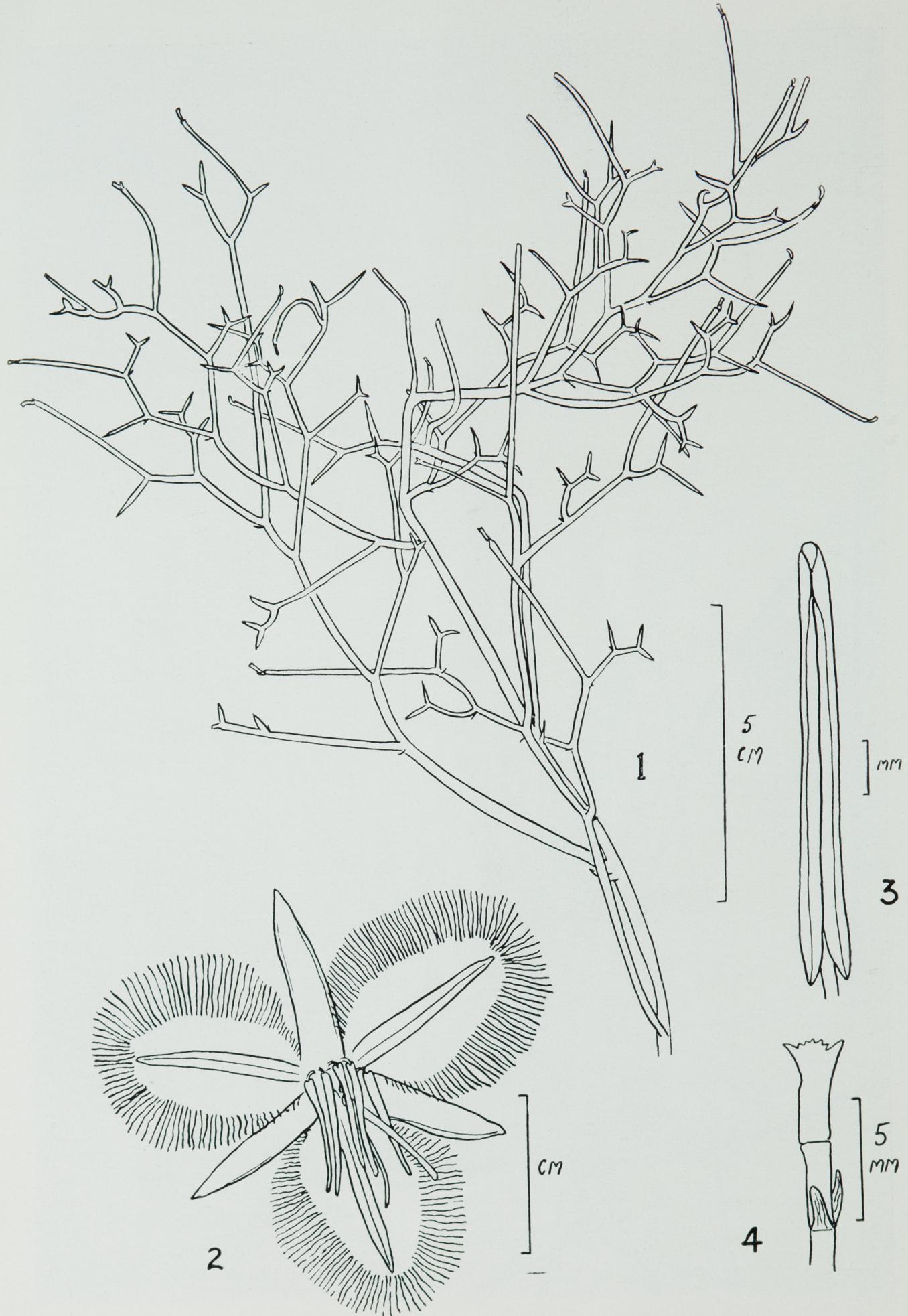


Fig. 7.—*Thysanotus spiniger* N. H. Brittan.

1.—Part of whole plant, N. H. Brittan 55/13. 2.—Flower N. H. Brittan 58/39 holotype. 3.—Detail of stamen N. H. Brittan 58/39 holotype. 4.—Detail of pedicel and bracts N. H. Brittan 58/39 holotype.

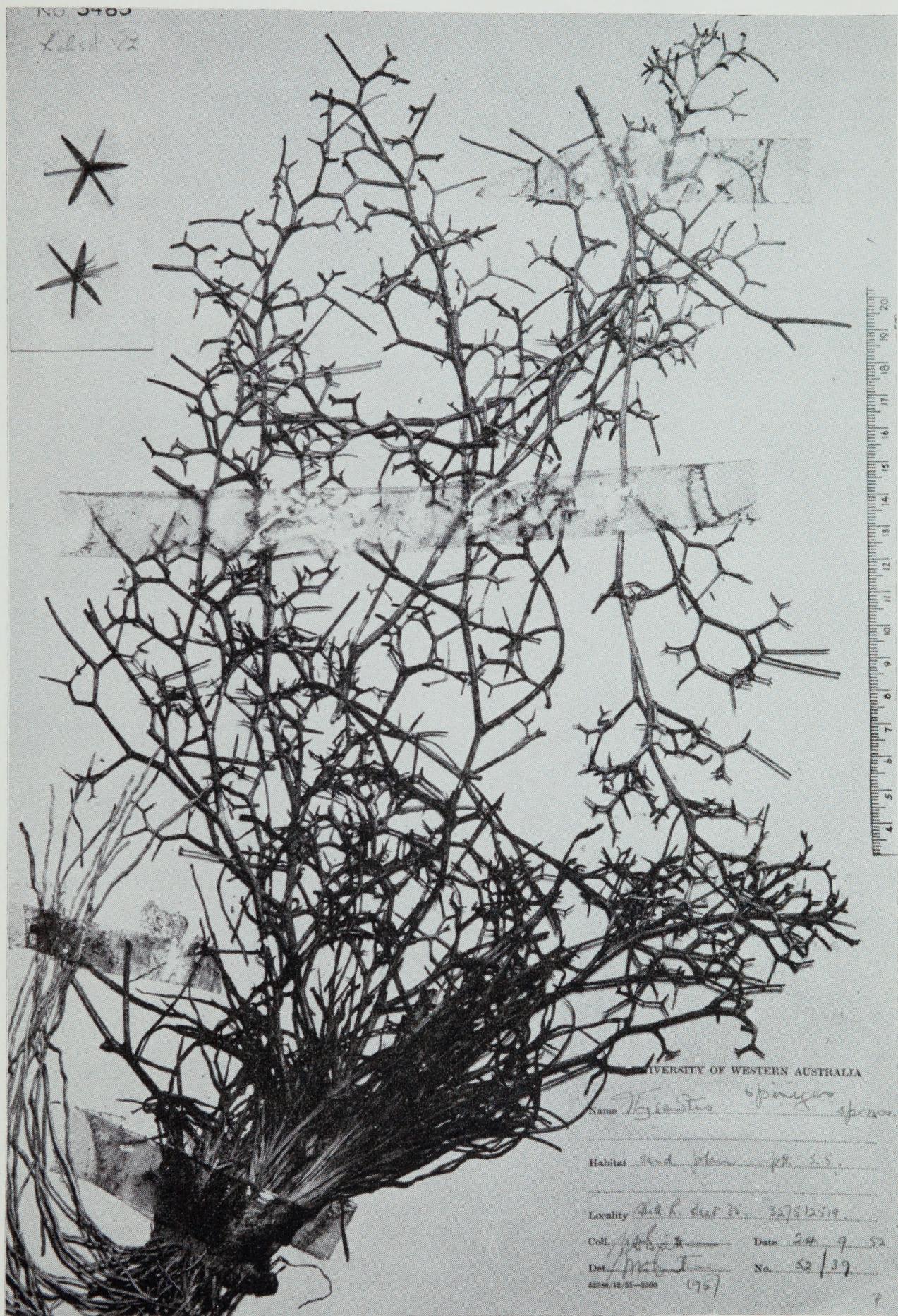


PLATE VII
Thysanotus spiniger N. H. Brittan holotype.

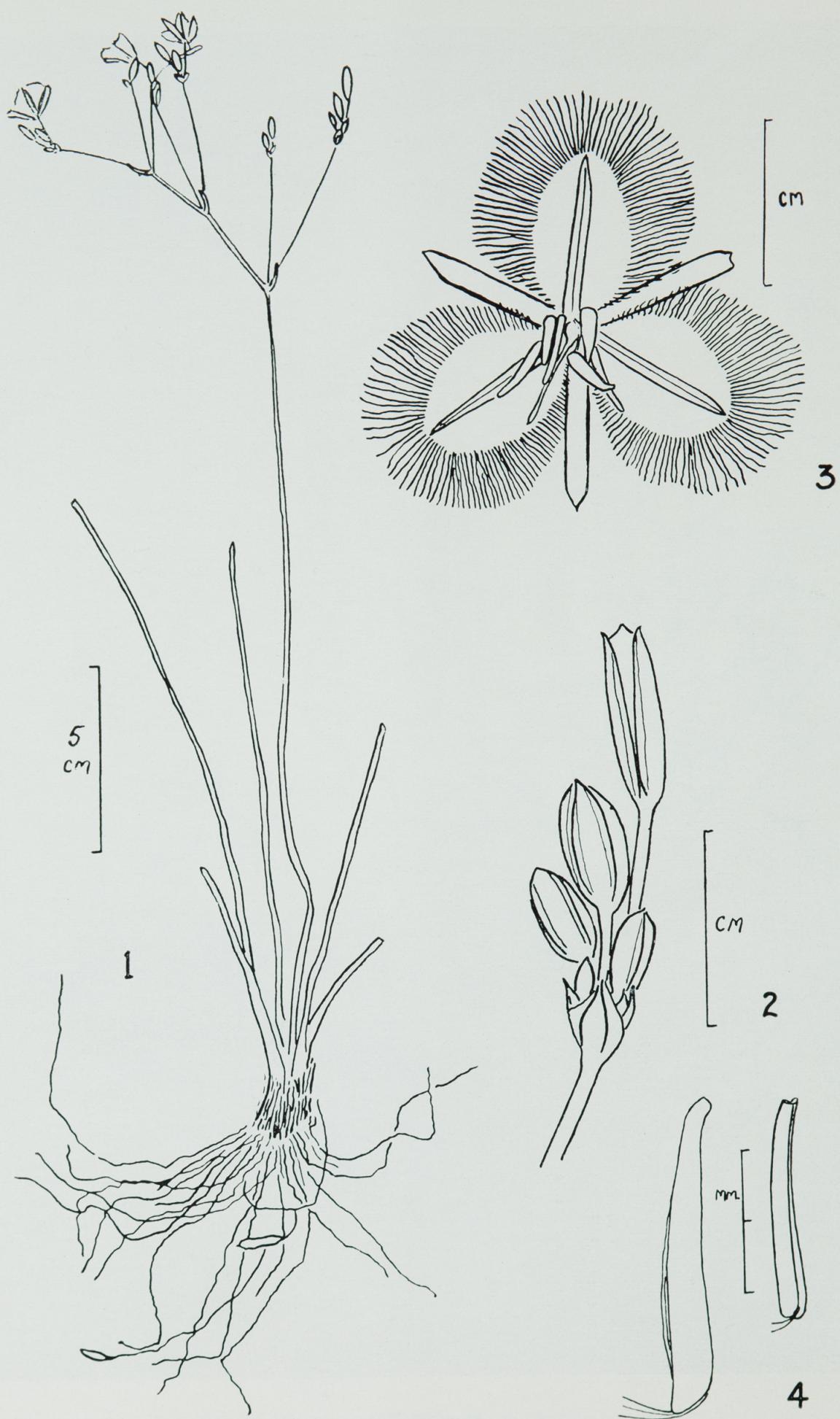


Fig. 8.—*Thysanotus cymosus* N. H. Brittan holotype.
1.—Whole plant. 2.—Detail of umbel. 3.—Flower. 4.—Detail of stamens.



PLATE VIII
Thysanotus cymosus N. H. Brittan holotype.

3.—The genus *Cethagus* Thorell (Mygalomorphae : Macrothelinae)

By Barbara York Main*

Manuscript received—10th December, 1959

The Macrothelinae occurring in Australia are reviewed. The species *Stenygrocercus broomi* Hogg and *Palaevagrus fugax* Simon are shown to be con-generic with *Cethagus lugubris* Thorell. *Cethagus*, the prior name therefore stands for the genus. *Macrothele aculeata* Urquhart is shown to be a misidentified Ctenizid. The New Caledonian species, *Stenygrocercus silvicola* (Simon) is also considered to belong in the genus *Cethagus*. Natural history notes are also recorded for *Cethagus fugax* (Simon).

Introduction

In the group Macrothelinae (Family Dipluridae, Sub-family Macrothelinae), four genera, each with one species, have been recorded as occurring in Australia. These are: *Cethagus lugubris* Thorell (1881), *Macrothele aculeata* Urquhart (1893), *Stenygrocercus broomi* Hogg (1901) and *Palaevagrus fugax* Simon (1908). Examination and comparison of the type specimens of *C. lugubris*, *S. broomi* and *P. fugax* shows that these species are con-generic. Thorell's name *Cethagus* is the prior name and *Palaevagrus* becomes a synonym. *Stenygrocercus silvicola* (Simon) from New Caledonia was originally placed in the genus *Macrothele* (Simon 1889) but Simon later made it the type species of the new genus *Stenygrocercus* (Simon 1892). This species also should be included in the genus *Cethagus*. Berland (1924) attributed a male specimen to this species. The specimen described by Urquhart (1893) as *Macrothele aculeata* was a Ctenizid (to be discussed in another paper).

The present paper redefines the genus *Cethagus*, reviews the Australian species, describes the male of *C. fugax* and records natural history observations.

Taxonomy

Simon (1892, p. 185) suggested that *Cethagus* was probably a synonym of either *Atrax* or *Hadronephe* and Roewer (1942) placed *Cethagus* with the Atraceae. Genera of the Atraceae have relatively short, bluntly pointed posterior spinnerets and teeth on both margins of the cheliceral furrow whereas *Cethagus* has long tapering posterior spinnerets and teeth on the inner margin of the cheliceral furrow only (except a few small basal teeth on outer margin). Roewer (1942) lists *Stanwellia* Rainbow and Pulleine, with the Macrothleae; but the presence of a double row of teeth on the upper tarsal claws establishes its position in the sub-family Dipjurinae.

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Cethagus Thorell 1881

Type species: *Cethagus lugubris* Thorell 1881.
References and Synonymy†

Cethagus Thorell 1881. Ann. Mus. Civ. Genova. 17, pp. 240-1 (nov. gen.).

Simon 1892. Hist. Nat. des Araign. 1, pp. 183, 186.

Hogg 1901. Proc. Zool. Soc. Lond. 1901 (2), p. 265.

Bonnet 1956. Bibliographia Araneorum (Toulouse), p. 1027.

Macrothele (in part) Simon 1888. Ann. Soc. Ent. France (6) 8, p. 245.

Palaevagrus Simon 1908. Fauna Südwest-Austral. 1, p. 365 (nov. gen.).

Bonnet 1958. Bibliographia Araneorum (Toulouse), p. 3301.

Stenygrocercus Simon 1892. Hist. Nat. des Araign. 1, pp. 182, 183, 185 (nov. gen.).

Simon 1903. Hist. Nat. des Araign. (Supplement) p. 968.

Hogg 1901. Proc. Zool. Soc. Lond. 1901 (2), pp. 265, 270.

Berland 1924. Nœva Caledonia (Sarasin and Roux), pp. 173-4.

Bonnet 1958. Bibliographia Araneorum (Toulouse), p. 4157.

Diagnosis.—Flattish carapace with the eyes raised in a small transverse compact group. Pit-like fovea sometimes distinctly recurved. Geniculate chelicerae, teeth on inner margin of furrow only (except sometimes a few small basal teeth on outer margin). Labium almost square, no cuspules. Maxillæ without cuspules or spinules. Legs without scopulae in female, male with sparse scopulae. All tarsi with ventral spines. Posterior spinnerets long and flexible, but without subarticulations and not exceeding length of abdomen. Male lacks any processes on the legs.

Cethagus lugubris Thorell 1881

Cethagus lugubris Thorell 1881. Ann. Mus. Civ. Genova. 17, pp. 241-3.

Simon 1892. Hist. Nat. Araign. 1, p. 186.

Hogg 1901. Proc. Zool. Soc. London 1901 (2), p. 265.

Bonnet 1956. Bibliographia Araneorum (Toulouse), p. 1027.

†In the literature listed here and also under the species names references which are to catalogue lists are only given for Bonnet, which includes a comprehensive bibliography.

Types.—Three specimens comprising one female, one male in penultimate instar and one juvenile, in the Civic Museum Genova. Collected by L. M. D'Albertis in 1875 from Somerset, Cape York, Queensland. These specimens are in spirit, in the one vial, and are all in deteriorated condition as already reported by Thorell. All type specimens a deep reddish-purple (plum) colour with the maxillae and labium yellowish; abdomen without any dorsal pattern. Carapace length of female 8.0 mm, width 7.9 mm. This is thought to be the specimen described by Thorell. The carapace lengths of the immature male and juvenile specimens 6.5 mm and 5.0 mm respectively.

Two specimens in the author's collection, from Reedys and Cundeelee, Western Australia were also a deep purple colour in life and are tentatively identified as *lugubris*. The present author also collected four small specimens which probably belong to *lugubris*, in the MacPherson Ranges, New South Wales, near the south base of Mt. Lindsay, nearly two miles south of the State boundary on the road which passes through the border check.

No male specimens are known.

Cethegus broomi (Hogg) 1901

Stenycercus broomi Hogg, 1901. Proc. Zool. Soc. Lond. 1901 (2), pp. 270-3. Text-fig. 38.

Bonnet 1958. Bibliographia Araneorum (Toulouse), p. 4157.

Types.—One female and one juvenile in the British Museum of Natural History. Collected by Dr. Broome from Hillgrove, New South Wales. Specimens in spirit. Specimens a uniform dark brown. Abdomen of adult with a faint dorsal pattern of three chevrons. Carapace length of adult 9.0 mm, width 7.0 mm. Spinnerets of the adult specimen asymmetrical, right posterior spinneret shorter than left and appears to have been regenerated.

No male specimens are known.

Cethegus fugax (Simon) 1908

Palaevagrus fugax Simon, 1908. Fauna Südwest-Austral. 1, p. 365.

Bonnet, 1958. Bibliographia Araneorum (Toulouse), p. 3301.

Types.—Two specimens mentioned by Simon in his description of *Palaevagrus fugax*, from Lion Mill and Geraldton, Western Australia. Collected by the "Hamburger südwest-australische Forschungreise, 1905." The Geraldton specimen (examined by the author) now in the Museum at Berlin.

The specimen seen was a juvenile in spirit. Carapace length 4.0 mm. Generally a uniform light brown colour. Male allotype (herein designated) collected by the author, 3 miles east of Byford on 8th March, 1959. To be deposited in the Western Australian Museum.

Diagnosis.—Female: Indistinguishable from *broomi* and also from *lugubris* except possibly on colour. *Fugax* in life a light dusty brown colour. Possibly *lugubris* tends to have more numerous and heavier tarsal spines than *fugax*

but more specimens of *lugubris* require examination. Size variable. The following measurements given are of a female specimen, from the same locality as allotype, selected from the author's collection, to be given to the Western Australian Museum. Carapace length, 5.3 mm. Leg lengths respectively: I, 10.8 mm; II, 11.5 mm; III, 13.6 mm; IV, 17.0 mm; Palp, 7.8 mm. The leg formula (obtained by dividing the length of the leg by the length of the carapace) is thus as follows:

| 4 | 3 | 2 | 1 |
|-----|-----|-----|-----|
| 3.4 | 2.6 | 2.2 | 2.0 |

Spines are present on the lateral edges of the ventral aspect of all tarsi including palp tarsus, ventrally on metatarsus I and II, and on all aspects of metatarsi III and IV. All segments of all legs have numerous long hairs and bristles. In many instances the bristles are scarcely distinguishable from spines. The largest specimens observed had a carapace length of 6.0 mm. A live specimen is illustrated in Fig. 1, Fig. 2A gives dorsal view of animal, Fig. 2B profile aspect, Fig. 2C sternum, Fig. 2D, spinnerets.



Fig. 1.—*Cethegus fugax* (Simon), female specimen.
Photograph B. Y. Main.

Male.—Apart from sexually functional external characters, such as the male palp, dimorphism is not conspicuous. However the legs are proportionately longer (see formula below) and scopulae are well developed on the tarsi of the third and fourth legs and divided by a medial line of bristles. A few scopulate hairs present on tarsi of first and second legs. Male animals brown, slightly darker than females, with a faint golden sheen on hairs in life.

Carapace length of allotype 6.0 mm, of other specimens examined 5.0, 5.3, 5.6, 5.7, 5.7 and 5.9 mm. Palp as in Fig. 2E. First legs (Fig. 2F) and second legs without any modifications or pro-

cesses. Leg lengths of allotype as follows: I, 16.7 mm; II, 17.5 mm; III, 19.6 mm; IV, 24.1 mm. Leg formula:

| 4 | 3 | 2 | 1 |
|-----|-----|-----|-----|
| 4.0 | 3.3 | 2.9 | 2.8 |

Spines are present on the same leg segments as in the female. No spines present on palp. Legs generally with dense covering of long hairs and bristles.

Localities of specimens in author's collection.

Females and juveniles.—WESTERN AUSTRALIA: Balladonia, 43 miles east on Eyre Highway, 1; Bullsbrook, 7 miles from on Chittering Valley Road, 1; Byford, 3 miles east, 5; Canna, 1; Carilla, 2; Coolgardie, 27 miles west, 1; Gidgegannup, 1; Merredin, 1; Mokine, 3; Moonera Tank, 13 miles west, 1; Morawa, 1; Norseman, 1; Norseman, 3 miles south, 1; Paynes Find, 4 miles west, 1; Perth, 15 miles east on Red Hill Road, 1; Queen Victoria Spring, 11 miles South West, 1; Wialki, 1; Widgiemooltha, 1; Zanthus, 6 miles west, 1. SOUTH AUSTRALIA: Between Port Kenny and Streaky Bay, 2; Streaky Bay, 3; Warrachie, 3; Wilpena Pound, 1.

Males.—WESTERN AUSTRALIA: Beverley, 1; Byford, 3 miles east, 6 (includes allotype).

Natural History

Habitat.—Specimens of *Cethegus fugax* have been observed in varying types of habitats. In the southern part of the sclerophyllous (jarrah) forest region (see Gardner 1944) of Western Australia they occur in greater density than anywhere else. Here webs are found on lightly lateritic soils, attached to logs and small herbs and also along the barren banks of roads where they sometimes present an almost continuous shimmering blanket of web several chains in extent. Further east in the savannah and sclerophyllous woodland zones (Gardner 1944) only isolated webs have been sighted. Again they are usually associated with gravelly or stony soils or sometimes yellow sands. On the Nullarbor Plain and Eyre Peninsula, burrows occur on stony limestone soil which has light cover of litter. In south-western Western Australia *Cethegus* has not been found in the wet karri forest (Mesophytic Forest region of Gardner) nor in the wetter southern part of the jarrah region, which have a dense understory and ground cover.

The burrows of *Cethegus lugubris* observed by the author in the MacPherson Ranges were amongst exposed roots of trees in an overhanging bank of a valley in the jungle.

Life History.—Life history data are only available for *C. fugax* and this is very slight. J. A. L. Watson found a male specimen under a stone, in June 1957. The author collected five recently matured male specimens from their burrows near Byford on 8th March, 1959. Presumably these specimens would have run with the onset of autumn rain in April or May. A sixth male was collected from Byford on 31st August, 1959. It is thought that this animal remained in its burrow until the end of winter, due to the extraordinarily dry season. No egg cocoons have

been observed but juvenile specimens were seen in two adult burrows at Mokine on 23rd March, 1959. It is assumed that these hatched from egg cocoons during the summer. From analogy with life history patterns of other Mygalomorphae where the seasonal sequence has been documented it is suggested that for *Cethegus fugax* the seasonal behaviour would be as follows: Mating in late autumn through to early winter, i.e., depending on onset of rain with appropriate temperature; egg laying late spring to early summer, eggs hatch mid-summer and juveniles vacate female burrows after first autumn or winter rains.

Since *C. lugubris* occurs in a region of summer rain with a dry winter period it is probably a summer mating spider.

Web and burrow.—The web of *Cethegus fugax* consists of a central portion of vertical soil-covered strands. These are attached at their upper ends to low shrubs, the bases of trees, projections of soil or rocks, to the sides of logs or overhang in banks, depending on the habitat. Such strands formed from the silk bound bundles of soil excavated from the burrow present a dense curtain like structure. Radiating from this section of the web are numerous threads extending for several inches. These unsoiled threads acting as "trap-lines" for catching prey, form an extraordinarily dense mass, within which are several funnel like tubes opening near the surface. Within the centre of the web or below the ground these tubes unite and terminate in a single poorly defined burrow, lacking any plastering, reinforcement or closely woven silk lining to the walls. Rejectamenta and cast skins are frequently found in the older parts of the webs. Burrows of penultimate instar and mature males have no "trap-lines" and the untidy mass of partly collapsed soil coated threads appears like an unoccupied nest. Also the burrow terminates in a symmetrical, smooth walled tube, in which possibly the male may seal itself off during the penultimate instar.

Specimens of *Cethegus lugubris*, collected by the author were taken from webs similar in structure to those of *fugax*.

Discussion

The occurrence of *Cethegus* in south western Australia is of interest since it is the only Macrothelinae genus known to occur west of the Eyre Peninsula. *Hadronyche* has been collected by the author (unpublished) in the Flinders Ranges and Eyre Peninsula in South Australia. Further east the Macrothelinae are a prominent component of the Mygalomorph fauna extending from Cape York to Tasmania. It is also of interest that the genus *Cethegus* has a continent-wide range and occurs in varied habitats.

Acknowledgments

Collection of specimens considered in the preparation of this paper was done with the help of a Research Grant from the University of Western Australia. A visit to the British Museum (Natural History) was made possible through an International Federation of Uni-

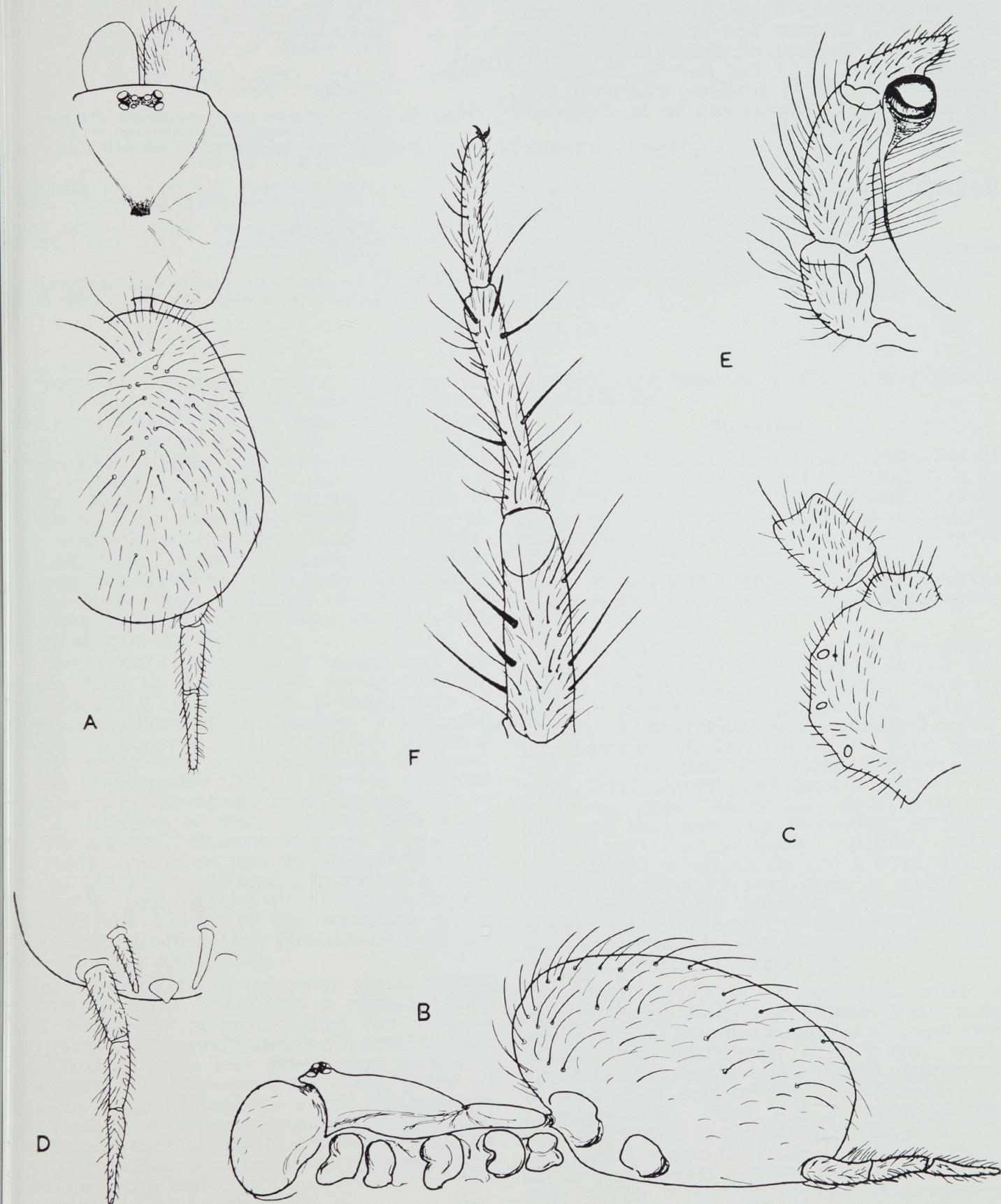


Fig. 2.—*Cethegus fugax* (Simon).

A, dorsal aspect, female. B, left lateral aspect, female. C., sternum, labium, right maxilla, female. D, spiniferets, female. E, right palp retrolateral aspect, male. F, tarsus, metatarsus, tibia of right leg, male.

versity Women Fellowship (Alice Hamilton Fellowship 1958). The assistance and working facilities given by the staff of the Arachnida Department of the British Museum of Natural History was greatly appreciated. Dr. W. Crome of the Berlin Museum and Professor Tortonese of the Civic Museum of Genoa kindly loaned type specimens. A. J. Lee and W. B. Malcolm assisted in the field by providing transport. C. A. Gardner, J. A. L. Watson and W. H. Butler are thanked for specimens.

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Part 2

4.—Patterns of Life on Rocky Shores

Presidential Address, 1959

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I must at the outset explain my choice of title. At first sight this may appear more suitable for a popular lecture than for the Presidential Address to a scientific society. It is nevertheless carefully phrased to explain what I want to speak about. In the literature on littoral biology the term constantly used is 'zonation'. The paper most commonly referred to is one by T. A. and Anne Stephenson (1949) entitled, "The universal features of zonation between tide-marks on rocky shores", and many papers have been published describing the zonation of animal and plant life on rocky shores all over the world.

I have made such studies myself and am hardly likely to be accused of not appreciating their value if I appear critical in this attempt to examine the basis of such studies. I think the descriptive material supplied by these papers is of very great value and the attempt, expressed by the Stephenson's title, to discover universal features is an essentially scientific approach in that it attempts to relate observed facts in an orderly manner. However it seems to me that the study of zonation and the attempt to fit all littoral life into a universal pattern has become an end in itself, instead of a means to understanding the biology of the organisms which collectively produce this zonation and of the causal factors responsible.

Any study of the life of rocky shores reveals not only patterns of zonation in relation to sea level but other patterns which are just as important to an understanding of causal factors, and some of these may prove more accessible to experimental analysis. Moreover, study of patterns of life on rocky shores can give valuable information of general biological application. The littoral environment is a microcosm and as such is particularly suited to study if the right questions are asked.

In a presidential address one may be permitted to speculate in a way which might be out

of place in a rigorous scientific paper; this I propose to do.

Zonation

The fact that the animal and plant life of rocky shores displays a vertical zonation is at once obvious to anyone visiting a sloping rocky shore; it is less evident but just as real on the characteristic stepped limestone shores of south western Australia.

Two examples will serve to illustrate the type of distribution which has been described in most parts of the world.

1. Cape Leeuwin (lat. 34°S) at the southwesternmost point of Western Australia has sloping granite-gneiss rocks with moderate exposure to wave action at the point surveyed. The vertical distribution of the principal organisms found here is shown in Fig. 1. Below mean low water the rock is encrusted with coralline algae, lithothamnion, and there is a thick cover of brown algae. Above low water mark the dominant organisms are successively a limpet (*Patellanax*), a barnacle, another limpet (*Notoacmea*), a periwinkle, and a black film of blue-green algae. Among these a number of other organisms are common, each at its preferred level. The height to which the barnacle zone, and those above it, extends varies greatly with the aspect of the rock face.

2. Poste Lafayette on the east coast of Mauritius (lat. 20°S) has sloping basalt rocks and is exposed to strong, almost continuous wave action. The middle part (1 to 6 feet) above low water has many small regular depressions in which sea urchins live (*Echinometra* and *Stomopneustes*). From Fig. 2 it will be seen that again there is a fairly sharp upper limit to the larger algae in bulk, though individual plants occur higher. Above this there is a broad zone where three sea urchins (*Echinometra*, *Colobocentrotus*, and *Stomopneustes*) are the principal organisms, although three species of limpet are also common and a number of other organisms are present in smaller numbers, including barnacles. A narrow band with very

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few animals and a sparse growth of small algae is succeeded above by a film of blue-green algae on which periwinkles browse. It may be noted that one limpet, *Patella chitonoides*, is strictly confined to the lower part of the sea urchin zone.

Both shores display a characteristic zonation. The organisms which are thus zoned are the algae, sedentary animals such as limpets, and some rather more active animals such as the periwinkles. There are also common shore animals, grapsoid crabs and certain small fish which are much more active and move up and down with the water. With the exception of the last group all the animals and plants have their own specific levels where they are most abundant, thus forming a horizontal band along the shore. Often the numbers tail off gradually above and below, but in many cases their upper or lower limit is quite sharply demarcated. Sometimes a number of organisms share a common upper or lower limit; it is not just that individual species have their preferred levels on

valuable review paper, by Doty (1957), only became available to me after delivery of this address.

It is now generally agreed that shore zonation is "not a product of mere association or gregariousness, but that it is related to the differing tolerance by the organisms of the environmental factors that vary from high-water mark to low water" (Southward 1958). It is implicit in Stephenson's scheme of universal zonation that this is so. There can be little doubt that these variables acting directly or indirectly on the plants and animals do ultimately cause the observed zonation.

Many recent studies of life on rocky shores have concentrated on typifying the zonations of geographic regions, and authors have tried to relate the observed zonation to Stephenson's universal scheme. This is undoubtedly a useful descriptive device, because it facilitates comparison between shores in many parts of the world, and there is no doubt that the broad features

TABLE I

| <i>A scheme for describing the zones of plant and animal life on rocky coasts (from Southward 1958)</i> | Extreme limit of spray or salt air | SUPRALITTORAL ZONE |
|---|--|--|
| Maritime land-lichens and salt-tolerant phanerogams | Extreme limit washed by tides or waves | SUPRALITTORAL FRINGE |
| Marine lichens and certain littorinids | Level not washed by all tides | MIDLITTORAL ZONE |
| Barnacles, limpets, green algae, smaller brown algae and some red algae | Level not exposed by all tides | INTERTIDAL ZONE OR LITTORAL ZONE |
| Large brown algae, many red algae and calcareous algae: sometimes marine phanerogams | Extreme level uncovered by tides | INFRALITTORAL FRINGE |
| Some large brown algae, red algae and marine phanerogams | Level at which there is not enough light for photosynthesis of algae | INFRALITTORAL ZONE |

the shore, but a number of animals and plants seem to share a common preference for a particular level.

This zonation has common features shared by shores all over the world. Littorinid molluscs colonise the upper rocks where they often get only spray or splash. Immediately below them, washed by the waves at every tide, there are usually dense colonies of barnacles. A more varied assortment of animals and plants commonly takes over lower down, and at about mean low water certain large algae (*Laminaria* and *Ecklonia*) become dominant; this last change is particularly well defined on our granite shores.

The fact that these broad zones can be recognised on rocky shores almost anywhere throughout the world has led T. A. and A. Stephenson (1949) to propose their 'universal' scheme of zonation. This scheme has been very generally adopted by writers on intertidal biology, though there has been disagreement about the exact limits of the zones and the names applied to them. The scheme is summarised in the accompanying table from Southward (1958) who has recently reviewed the whole subject of zonation on rocky shores. Another

of the zonation can be recognized in most places. There are however certain dangers attendant on this approach, and these I want to examine briefly.

Perhaps the most serious danger is that description of the zonation can easily become an end in itself and so discourage further study. The synecological approach will be particularly unprofitable if it does not point the way to an understanding of the causes of zonation. Causes are considered by Southward (1958) and formed the principal subject of an interesting discussion by Stephenson (1943) and others at a symposium of the Linnean Society of London. However much detailed work on individual species will be needed before there can be a full understanding of the complex patterns on most shores.

A second danger is that by fitting observed patterns into a general scheme real differences may be obscured; differences which may in themselves be very informative. The difference between the zonation of wave beaten and sheltered shores has received considerable attention, and the information derived from such comparisons has proved valuable. There

are however other physical variables which influence the distribution of shore animals. These include: the mechanical action of the waves, the pounding and tearing action of which inhibits some organisms and favours others; the angle of slope of the shore; the nature of the substrate, whether hard or soft, porous or relatively impermeable to both water and filamentous algae; the presence of crevices in the rock. Perhaps these are only 'modifying factors' for zonation, but all are a significant part of the environment, and as such may be the immediate factors which favour one species rather than another.

More subtle however is the danger that just because the zonation can usefully be described by a universal nomenclature, the vertical movement of the water line on which this system is based may be thought to produce its effect in a uniform manner. On the one hand movement of the water line is itself complex, varying both in range and periodicity and it would be surprising if the results it produced on the shore environment were uniform. I will return to this later. On the other hand the many species which collectively produce the zonation respond in different ways to the physical components of the varying weather of the shore: temperature, insolation, and moisture.

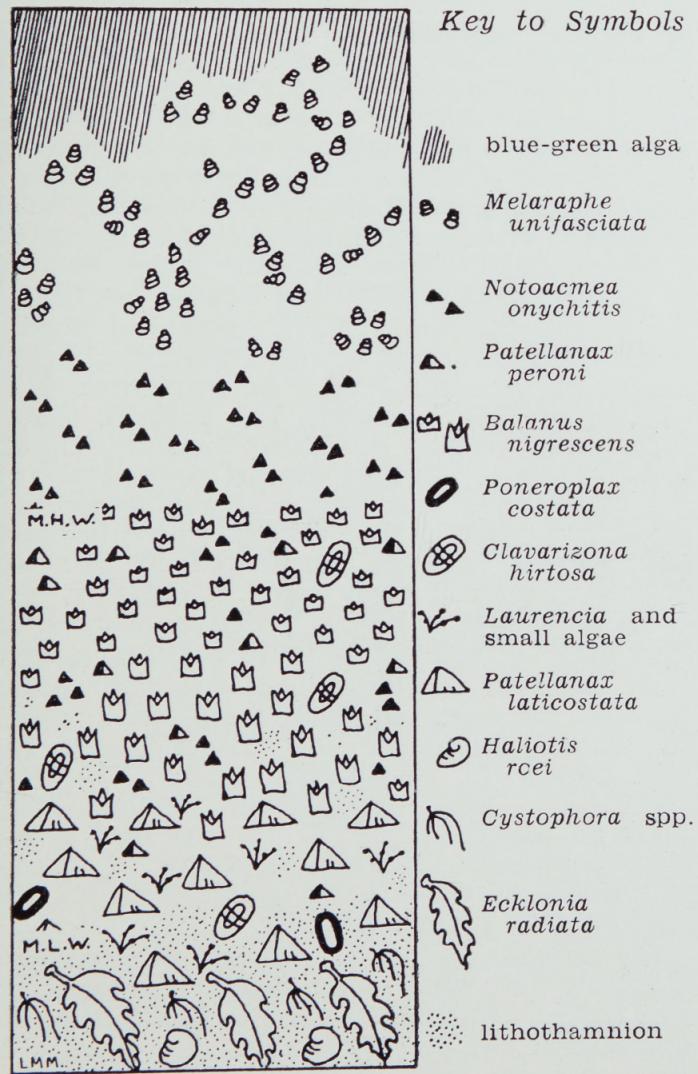


Fig. 1.—Cape Leeuwin, Western Australia. The littoral fauna and flora of a sloping rock surface with moderate exposure to wave action.

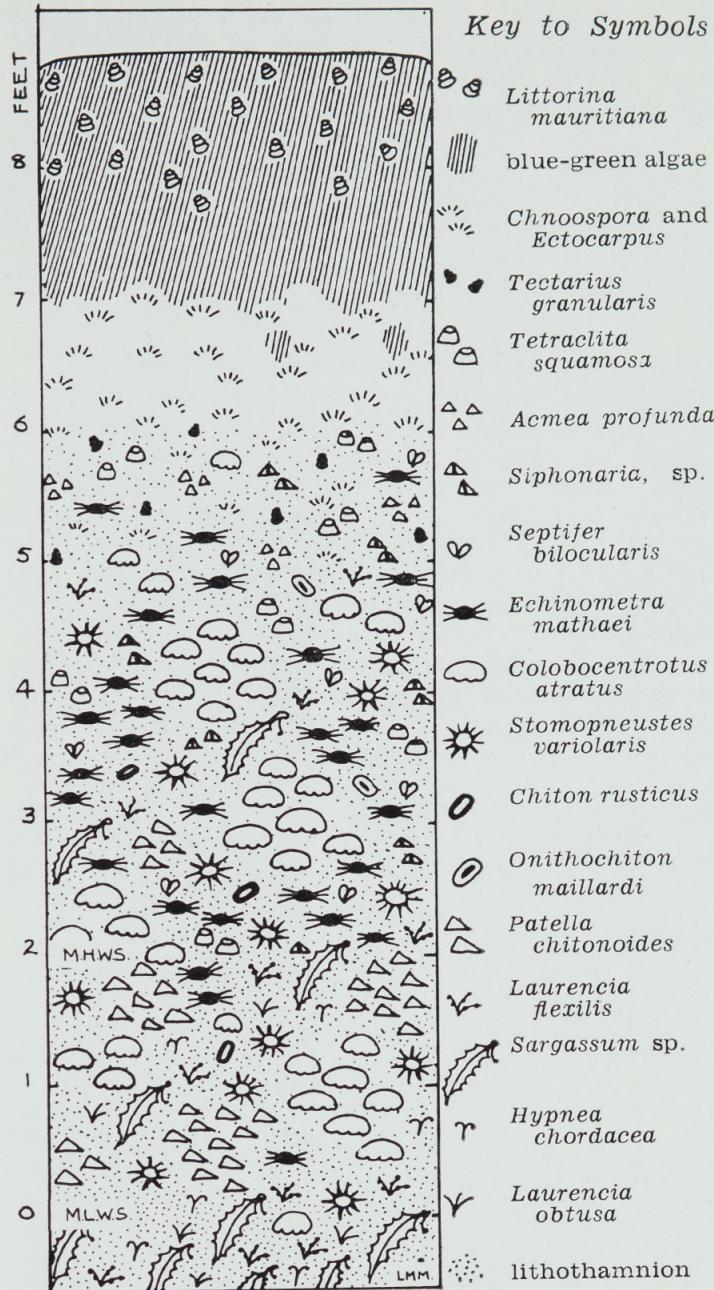


Fig. 2.—Poste Lafayette, Mauritius. The littoral fauna and flora of a sloping rock surface exposed to constant wave action.

A fourth danger in the zonal approach is that it is static. The very uniformity recognised in the zonation implies a permanence. But the individual organisms, and the groupings of these, which collectively make up the zones are transient and study of their dynamic interactions is more likely to be informative than observation of apparently static distributions.

This has been brought home to me forcibly recently. Exceptionally low tides and calm seas in January of this year destroyed the entire animal life of certain reef platforms on our west coast (Hodgkin 1959). It is too early yet to know whether these species will re-establish themselves, but other species of animals and plants have already replaced them in the space left vacant after the catastrophe.

This is a particularly striking example of sudden change in distribution, but there are many features of the patterns of shore life which cannot be adequately explained in terms

of the physical attributes of environment alone and require an understanding of the interrelations of the animals and plants themselves.

I propose first to consider briefly the water movements which cause the characteristic fluctuation in physical environment—the weather of the shore—and then to discuss some of the immediate factors which determine the patterns of life on rocky shores, more especially interrelations of organisms.

Water Movements and Zonation

It is, I think, unfortunate that the zonation is so often called 'intertidal', or 'zonation between tide-marks' to use Stephenson's phraseology. The term 'tide' and its derivatives have precise meanings; the shore zonation normally extends well beyond the limits of the tides, the supra-littoral fringe is a product of wind and waves, and the use of these terms is therefore inaccurate.

They are also misleading because they place an undue emphasis on the tidal factor in zonation. Stephenson and Stephenson (1949) state that: 'The primary cause of it [zonation] is the existence of an interface between air and water'. But, as stressed by Southward (1958), it is 'rise and fall of the water line produced by the tides or waves, or both [which] must be regarded as the primary cause of the observed patterns of zonation'.

The emphasis on tides as the ultimate cause of zonation probably derives from the fact that most studies have been made on shores with a considerable tidal range. The zonation in such places is a 'tidal zonation', though modified by the degree of wave action. In the Mediterranean, which is almost tideless, or in the growth on a ship's hull the plants and animals are also clearly zoned. The exposed Mauritius shore described above is a good example of 'wave-zonation'—one caused mainly by continuous wave action. Here the mid-littoral zone has three times the vertical range of the tides. The sheltered shores of Mauritius have a totally different fauna and flora, and the littoral has a vertical range which corresponds to the small tidal range. Again this is a 'tidal zonation'.

The 'climate' of these two types of shore will obviously be very different. The difference is particularly striking in tropics and subtropics where the shore is subject to intense heating during the day. In the absence of continuous wave action, tropical shores have a short turf of small algae or are dominated by animals; there is not the heavy cover of large brown algae so common on temperate shores. The importance of this 'latitudinal effect' may be noted here in passing.

The immediate physical factors which constitute the climate of the shore (temperature, insolation, and wetting and drying) vary with position in the vertical range of movement of the water line. However, this movement of the water line is complex. The waves and tides which cause it vary independently both in vertical range and periodicity. Waves have periods of seconds and their amplitude varies irregularly. Tidal fluctuations have periods of 12 and

24 hours, 14 and 28 days and recur with great regularity. Diurnal and semi-diurnal tides are different in their influence on the relative duration of emergence and immersion and there are longer period seasonal and irregular fluctuations of level. Even the time of low tide has been shown to be important (Lawson 1957).

Before leaving the subject of zonation let me summarise the position as I see it. On any shore where there is water movement, however caused, the major zones which have been generally recognised certainly exist. However variability of the biological material, latitudinal effect, and the lack of uniformity of water movement, make it impossible to define precisely zone boundaries which will have universal application. To do so is to impose an exact classification where none is warranted, one which can obscure data that are important to an understanding of the relation of organisms to their environment.

Causes of Shore Patterns

Andrewartha and Birch in their book 'The Distribution and Abundance of Animals' divide the environment of an animal into four components: weather, food, other animals and organisms causing disease, a place in which to live. Their discussion relates mainly to terrestrial animals, but I hope to show that this analysis of environment is valuable also in the study of littoral populations. I am not suggesting that concepts derived from a study of terrestrial animals should be carried over to the littoral environment without careful examination and without due weight being given to the peculiarities of the situation. One such peculiarity is that littoral populations occupy a band which may be of great length, but is seldom more than a few yards in width. Another is that dispersal of immature stages is often largely passive.

Andrewartha and Birch stress the need to study the interaction between individual species and their environment; I do not question the wisdom of this approach, but I think that in some cases we may profitably consider the animals of small phyletic groups collectively and also sometimes the ecological replacements of particular animals. For example, both barnacles and limpets may be considered in this way. Several species of each occur at different levels or in particular habitats, while on other shores they may be replaced by quite different animals.

Of the four components of the environment, weather has received most attention in studies on littoral organisms (e.g. Broekhuysen 1940, and review in Southward 1958). The other components were, food, other animals and a place in which to live. I propose now to consider particular animals, or groups of animals, in respect of these three components of their environment more especially.

My purpose is to discuss what information is available and what can usefully be sought that will help us to understand the distribution and abundance of these animals. I am afraid I shall not be very systematic about it. It is seldom possible to fit the animals neatly into any particular pigeon hole and, as I said at the outset, I propose to be speculative.

Larval Settlement and a Place in which to Live

The eggs and early stages of many shore organisms are distributed by the sea water; they are planktonic and have to settle on or attach to the rocks before they can feed and grow. The initial settlement may be just as important in determining the ultimate distribution of the animals and plants as influences which operate on the adult organisms.

I will give two examples. 'Most European species of barnacles have been shown to be gregarious; the cypris settles and metamorphoses most easily in areas inhabited by adults of the same species or a closely related one, or on substrata bearing traces of a former adult population' (Southward 1958). Thus settlement is not random, although new surfaces are of course colonised. Barnacle populations tend to be self perpetuating and dense stands result, in which few other animals live.

The limpet *Patelloidea alticostata* occurs alone over considerable areas of the intertidal platforms on our coast. In November 1954 a party of Zoology students cleared every limpet from four square yards of a reef platform at Rottnest Island. Before clearing there were 400 to 500 limpets per square yard and no other animals or plants on the rock. Within a few days of their removal there was a dense growth of filamentous algae which was replaced by coralline algae over the next few weeks.

Five years after the original clearing the limpets have still not fully re-established themselves. Some have managed to invade the area from the edges and a few have settled within it, but there is a thick growth of weed and the limpet population is still less than half that outside where there is no weed. The change in environment brought about by the establishment of the weed prevented settlement of young limpets. The limpet population like the barnacles is normally self-perpetuating, it excludes macroscopic algae and other animals and so maintains its own place in which to live.

The clearing experiment was repeated on a vastly greater scale by the catastrophe of which I spoke earlier. The entire population of *P. alticostata* was destroyed on certain platforms at Rottnest (January 1959). During the succeeding twelve months two pulmonate limpets have invaded the virgin fields of small algae (there is no coralline mat). Unlike *Patelloidea* these limpets lay non-planktonic eggs all the year round. It is too early yet to know what will be the final outcome.

Other examples of what appear to be self-perpetuating populations are seen with the large limpet *Patellanax laticostata* and the mutton fish *Haliotis roei*. These, with *P. alticostata*, two chitons and an anemone are the principal fauna of the outer edge of our intertidal limestone platforms. In some places all occur together, in others one is dominant to the almost total exclusion of the others, the rock is grazed bare of algal growth and takes a form characteristic of the species. In such places each *P. laticostata* has a smooth shallow channel of four or five times its own area and often continuous with those of its neighbours, and *Haliotis* occupies shallow depressions of about its own dimensions. So long as these forma-

tions persist they certainly favour the particular species just as the bare flat surface favours *P. alticostata*. These animals are not confined to such places, but they are much more abundant in them than elsewhere.

Two rather different examples of limitation by available places in which to live are afforded by another limpet and a sea urchin. *Patelloidea nigrosulcata* lives principally on the shells of other gastropods, chiefly the large limpet *Patellanax laticostata* and the mutton fish *Haliotis roei*. Usually there is only one *nigrosulcata* to each shell, and each shell is grazed bare. Although not every shell has its *nigrosulcata*, most have. Unoccupied shells are usually covered by a thick growth of algae—again an impenetrable jungle to a young limpet trying to find a place to settle.

The tropical sea urchin, *Echinometra mathaei* is abundant in the littoral on the wave-beaten rocky shores, such as the Mauritius shore described earlier and on the exposed west end of Rottnest. In such places it is confined to characteristic burrows in the rock; each animal has its own 'home'. On the Mauritius shores almost every potential home in the mid-littoral is occupied by a sea urchin and the density of population appears limited by the number of available homes. On the more exposed east coast *Stomopneustes* competes with *Echinometra* for these homes, but on the west coast *Echinometra* has the field to itself. In December 1957 there were vacant homes above the upper limit of distribution of the urchins; perhaps they are occupied at other seasons, but at that time they were above the level of continuous splash.

Weather

Weather is of such obvious importance in determining the distribution of intertidal animals that it has received much attention from workers on shore organisms. I do not want therefore to say much here, but will give a few examples of how weather limits the vertical range of organisms.

Above the intertidal platforms of our W.A. limestone shores the rock is generally vertical or overhanging. Here four or five feet of the rock face, the upper mid-littoral, is generally dominated by two limpets—*Notoacmea onychitis* and *Siphonaria luzonica*. These limpets establish their own 'homes' to which they return at low tide, but they evidently move house periodically. Each winter some of the larger limpets get so high on the rocks that when summer comes, with its lower sea level, calmer seas, and higher temperatures, the more adventurous animals are killed by heating and desiccation. In winter the sporelings of a variety of algae also establish themselves on this rock face. They never survive the lower sea level and calmer seas of spring. *Patelloidea alticostata* colonises the lower one foot of the rock, below *Notoacmea* and *Siphonaria*. I have never seen it dying here, but I suspect that its upper limit may be determined by the height to which a sufficiency of interstitial water is retained in the rock.

There is a similar seasonal mortality among juvenile barnacles on the granite rocks of our south-west. In early summer many empty

juvenile shells can be found on the rock above the main mass of *Balanus nigrescens*. The obvious assumption is that they have been unable to withstand heating and desiccation at the higher levels, however there is heavy predation by the whelk *Dicathais aegrota* and this is at least an important contributory cause of mortality.

Food

Andrewartha and Birch say that the number of animals in a population is seldom limited by shortage of food. The source of food of littoral animals is twofold: firstly the food which comes to them in suspension in the sea water and secondly the food which grows on the rocks. The amount of food available to suspension feeders certainly seems to affect their rate of growth, as indicated by the observations of Barnes and Powell (1950) but how far this is important in determining distribution in bulk is more difficult to decide. Barnacles, mussels, serpulids all commonly are packed tight, often entirely covering any surface on which they settle. The situation is very different for grazing animals. These feed actively, mainly on algae which grow on the rocks, and I suspect that for them food may often be a limiting factor.

Limpets furnish examples of natural populations which do 'consume a large proportion of the food available to them.' The populations of *Patelloida alticostata* of which I spoke earlier keep the algae on which they feed grazed down to bare rock, in fact they even remove rock particles in the process. Between 600 and 700 small to medium sized limpets per square yard seem to be the maximum population these resources can support. A population of this kind covers an area of platform at Green Island, Rottnest. But a small part of this same platform carries a population of no more than 200 large limpets per square yard, again to the exclusion of all other life. They are still fully utilising their food resources. Obviously food alone cannot here be limiting the actual numbers of animals, though it may limit the biomass which can be supported. The figures (Table II) suggest that recruitment to the population is greater in the first case than in the second and the subsequent history supports this. Perhaps I should have discussed this example under the heading 'Other animals of the same kind'. Here the natural situation approximates the experimental one in which the food is constantly replenished by the experimenter.

TABLE II

Numbers and Size distribution of *Patelloida alticostata* from $\frac{1}{4}$ sq. yard areas of rock

| Greatest diameter cm | <i>P. alticostata</i> in experimental areas: | | | | | | | |
|----------------------|--|-----|-----|-----|----|----|----|----|
| | A1 | A2 | B1 | B2 | C1 | C2 | D1 | D2 |
| 1.0 - 1.5 | 68 | — | 81 | — | 0 | 1 | 0 | 1 |
| 1.5 - 2.0 | 29 | — | 51 | — | 6 | 22 | 0 | 10 |
| 2.0 - 2.5 | 47 | — | 40 | — | 7 | 17 | 2 | 8 |
| 2.5 - 3.0 | 1 | — | 0 | — | 24 | 23 | 19 | 27 |
| 3.0 - 3.5 | 0 | — | 0 | — | 9 | 0 | 13 | 4 |
| Total measured | 145 | — | 172 | — | 46 | 68 | 34 | 50 |
| Total removed | 152 | 175 | 189 | 173 | 47 | 68 | 33 | 51 |

Regulation of animal numbers by other animals of the same kind would lead me to the dangerous ground of controversy over density dependent and density independent factors and this I do not propose to attempt to discuss.

Other Animals of Different Kinds

The two limpets *Notoacmea onychitis* and *Siphonaria luzonica* mentioned earlier under 'weather' share the same vertical zone either as a mixed population or with one or the other locally dominant, and they browse on the same sparse algal flora. Are they between them utilising the whole of the resources available to them? If they are, what ecological differences are there between them which enable them to live alongside one another instead of one replacing the other? I cannot suggest an answer here, but in analogous situation I can offer a partial answer.

There are two species of *Siphonaria* on Rottnest, *luzonica* and *baconi*. Sloping intertidal rock surfaces are the exception on W.A. limestone shores, but one such shore carries a mixed population of these two species. They are present side by side and appear to be utilising the same resources. However counts of the limpets show that *luzonica* predominates at the higher levels and *baconi* at the lower.

On the sloping rocks the two species live together in an environment that varies continuously. On the more usual stepped shores there is a separation of the two species; *luzonica* lives on the undercut face which is subject to drying at low water, *baconi* is seldom common but lives either at the foot of the undercut and onto the platform or submerged in small intertidal rock pools. In this case the area of overlap between the two species is small producing a zonation that is not evident on sloping rocks.

Where two species of animal utilise the same resources and the resources are limited, one animal may totally exclude the other, or they may both survive and share the resources. In the latter case they may intermingle freely or a patchy distribution of the two may result. (In laboratory experiments with insects these situations have all been achieved by suitable manipulation of the conditions).

I have already given an example of the first situation. *Patelloida alticostata* occupies considerable areas of platform from which all other animals are excluded. Given the right conditions *Haliotis roei* will cover the rock to the exclusion of every other animal; there is just such a population at Yanchep near the edge of the reef platform.

One might include the suspension feeders in this category too, because some of the barnacles, rock oysters, and serpulid worms occupy belts to the total exclusion of other macroscopic animals, but since the adults are completely sedentary the situation is very different. One might be justified in regarding them as plants, ecologically.

The second situation of two animals sharing the resources is illustrated by the two limpets *Notoacmea* and *S. luzonica* mentioned above, also by the urchins *Echinometra* and *Stomopneustes* on the east coast of Mauritius. The two species of *Siphonaria*, while sharing a

particular habitat have slightly different vertical ranges, as also have the two periwinkles *Melaraphe unifasciata* and *Tectarius rugosus* which inhabit the supralittoral fringe of our coastal rocks. It would be surprising if there were not also some difference in the requirements of the species mentioned first which are much less closely related to one another.

A careful analysis of the differing requirements of a large group of sympatric species of the predatory gastropod *Conus* is given by Kohn (1959).

The third situation, of a patchy distribution, may again be illustrated from Mauritius. Near low water level, on wave beaten shores, flat rock surfaces are colonised by a green alga. (*Chaetomorpha antennina*), a limpet (*Patella chitonoides*), and a sea urchin (*Colobocentrotus atratus*). In some situations their distribution is markedly patchy, one particular area of rock is covered with weed, another with limpets, and a third with urchins, in each case to the exclusion of all other macroscopic life.

I mentioned earlier a somewhat similar situation on some of our limestone platforms where patches of *Haliotis* sometimes alternate with *Patelloida alticostata*, each in its own place excluding all other animals. As stated there I think this is because the preferred microhabitats are not identical.

This explanation may apply also to the patchy distribution of limpet, sea urchin, and sea weed; their requirements may be slightly different, but although the areas involved are smaller, I think this case is more akin to that of the pure stands of *Patelloida alticostata* where the one animal utilises all the resources and excludes all other animals. I will return to this later.

I have spoken only of relatively simple situations in the interrelations of animals because these are most susceptible of analysis. However before leaving this subject I must mention briefly

TABLE III

Fauna of outer reef flat at different localities
Cape Vlaming is exposed to heavy wave action, Carnac West reef is less exposed, and Point Atwick is only moderately exposed

| | | |
|--------------|-----------|--------------|
| Rottnest I. | Carnac I. | Garden I. |
| Cape Vlaming | West reef | Point Atwick |

| | Coelenterata | | |
|--|--------------|-----|-----|
| <i>Isanemonia australis</i> | + | + | - |
| Amphineura | | | |
| <i>Poneroplaex costata</i> | + | + | - |
| <i>Clavarizonea hirtosa</i> | + | ++ | - |
| <i>Onithochiton occidentalis</i> | +++ | ++ | + |
| Gastropoda | | | |
| <i>Haliotis roei</i> | - | +++ | +++ |
| <i>Patellana x laticostata</i> | +++ | + | - |
| <i>Patelloida alticostata</i> | + | +++ | ++ |
| Crustacea | | | |
| <i>Balanus nigrescens</i> | +++ | - | - |
| Algae | | | |
| <i>lithothamnion</i> | ++ | +++ | + |
| large algae | + | + | +++ |
| Height of reef flat above M.L.W., feet | 2.0 | 1.2 | 0.5 |

TABLE IV

Fauna of outer reef flat at Yanclep.

The outer edge of the reef flat is straight, and all parts are equally exposed to wave action.

| Height of reef flat above M.L.W., feet | 0 | 0.8 | 1.5 | 2.5 | 4.0 |
|---|-----|-----|-----|-----|------|
| <i>Modiolus pulex</i> | - | - | - | - | ++++ |
| <i>Notoacmea onychitis</i> | - | - | + | ++ | + |
| <i>Patellanax peroni</i> | - | - | + | ++ | + |
| <i>Poneroplaex costata</i> | - | - | + | ++ | ++ |
| <i>Balanus nigrescens</i> | - | - | + | + | + |
| <i>Clavarizonea hirtosa</i> | - | +++ | ++ | ++ | - |
| <i>Patelloida alticostata</i> | - | +++ | +++ | - | - |
| <i>Haliotis roei</i> | + | +++ | +++ | + | - |
| <i>Onithochiton occidentalis</i> | - | ++ | - | - | - |
| <i>Isanemonia australis</i> | - | + | + | - | - |
| <i>Patellana x laticostata</i> | + | - | - | - | - |
| <i>lithothamnion</i> | + | +++ | + | - | - |
| blue-green algal film | - | - | + | ++ | - |
| large algae | +++ | - | + | - | - |

the more complex situation so often found on the shore where a number of species share a particular zone. This is well illustrated by what I call the 'outer edge fauna' of the Western Australian limestone reefs. Here, where the waves break hardest there is a mixed fauna usually with three or four macroscopic species really common and several other less common species. As shown by Tables III and IV the composition of the fauna varies from place to place, both with the degree of wave action and the level of the rock in the tidal range. Sometimes the mixed population is so dense that the rock is grazed bare. More often however coralline algae encrust the rock thickly, the same animals are scattered through this, and it provides macrohabitats which give refuge to a variety of smaller animal life.

Finally under this heading 'other animals of different kinds' I must mention predators. There is no dearth of predators in the littoral and there is plenty of evidence that whelks and cone shells, starfish and even gulls all take their toll. They may well be important in regulating the number of animals near the limits of their vertical range and thus help in maintenance of the zonation. I mentioned this in reference to *Balanus nigrescens* and *Dicathais aegrota* above. Barnes and Powell (1950) describe just such heavy predation on high level populations of barnacles on cleared rock surfaces on the Scottish coast. There is also no doubt that they attack these animals well within the preferred range, but what part they play in determining animal numbers and distribution is difficult to decide. Fischer-Piette (1935) describes how the whelk *Purpura lapillus* caused the relative abundance of barnacles and mussels in a mixed population to change. Initially barnacles were dominant, but heavy predation allowed mussels to replace them, the whelk then changed its feeding habits, the mussels were depleted and barnacles colonised the rocks again.

Dynamics of Shore Populations

This last example emphasises the dynamic character of shore populations. Both the shore zones and more localised groupings of animals and plants have a remarkable persistence, how-

ever they are certainly not static. A clear example of large scale change was given by the January catastrophe of which I spoke earlier. The same catastrophe resulted in the colonial anemone *Actineogeton* almost completely replacing all other life on one platform, only to be replaced in its turn by a mixed population more akin to that originally occupying the area. In another place the mussel *Septifer* replaced *Echinometra* for a time and there has been no sign yet of recolonisation by urchins. There have been other great changes and it will be instructive to see whether the original populations eventually re-establish themselves; whether in fact they represent relatively stable terminal communities (climates) or whether they are merely adventitious associations which may arise from time to time in this situation.

I gave earlier examples of seasonal changes in animal and plant populations on our limestone coast, I also mentioned the observation of Lawson (1957) that changes in the distribution of algae resulted from seasonal differences in time of lowest low water. These are of interest not only as evidence of constant change, but also because they indicate that these sort of changes may be important in producing the more persistent patterns.

But quite apart from catastrophes and seasonal fluctuations, shore populations are in dynamic rather than static equilibrium, and even though certain associations can be recognised as characteristic of particular levels the component parts are in constant flux. Shore animals and plants do not survive long individually, seldom more than a few years, they die or are destroyed by various agencies and are replaced by other organisms of the same or other kinds; there is constant competition for the available resources. Under these circumstances it is remarkable that shore communities do achieve a considerable measure of continuity. These communities are often so complex that any attempt at an analysis of the interrelations of the organisms is likely to be unprofitable. There are however simpler situations such as those discussed above where a knowledge of the biology of the few species present offers an opportunity to understand their interrelations.

One aspect of these situations bears amplification. I have described above examples of self-perpetuating populations covering considerable areas of rock. Patchy distributions may also be partly explained by the inability of interlopers to establish themselves. This is beautifully illustrated on some Mauritius shores where the urchin *Colobocentrotus* is found alone on certain rough limestone surfaces. In these urchin preserves of a few square yards in extent the only visible algae are those which cling to pinnacles of rock inaccessible to the urchins and the only other animals are a few daring interlopers belonging to more active species such as the turban shell *Turbo setosus*. Grazing pressure prevents macroscopic algae and young animals of other species from obtaining a foothold. T. A. and A. Stephenson (1949) illustrate the effect of brown algae in preventing settlement of barnacles.

Presumably in such cases the animal or plant has some slight ecological advantage over its neighbours. Such a situation, of two self-perpetuating populations each with slightly different ecological preferences must result in sharp boundaries between them. Again this is well illustrated from a Mauritius example. I found there that in passing from a more to a less wave-beaten situation *Colobocentrotus* was replaced by the limpet *Acmea profunda*, the two were mutually exclusive. In the more exposed part there was an equally sharp boundary in rising up from the band of *Colobocentrotus* to the *Acmea* above. Thus the vertical zonation showed a sharp boundary—a common feature of zonation.

Conclusion

I warned you I would speculate, and this I have done. I have put forward hypotheses to explain patterns of which I have spoken and I believe these are justified by the observations. To test them is quite another matter. However many of these problems are accessible to experiment in field or laboratory.

Much has been done with algae and also with some animals to find out how weather may determine their distribution on the shore, with valuable results. I do not doubt that weather is the principle component of the environment limiting the distribution of some animals. Clearly also shore climate ultimately determines the broad outlines of the zonation. I have tried however to show that observed patterns of distribution commonly result from more immediate factors: food and grazing pressure, available places in which to live, hazards of larval settlement, predation. These will be more difficult to study in the laboratory, particularly as they probably seldom act singly, but they should be accessible to analysis by relating laboratory and field experiment to observation in the field. But if this is to be done attention will have to be concentrated on individual species before the interrelations of complex associations can begin to be understood.

The littoral environment is certainly complex and there are considerable difficulties associated with study of its ecology. However I do not think it is any more complex or difficult of analysis than many terrestrial situations which ecologists have attacked with considerable success.

Acknowledgments

The investigations on which these observations are based were made with the help of a research grant from the University of Western Australia. I am indebted to many colleagues for the helpful discussions I have had with them on my theme and especially to Mrs. L. Marsh who has been associated with me in studies of the Western Australian littoral fauna.

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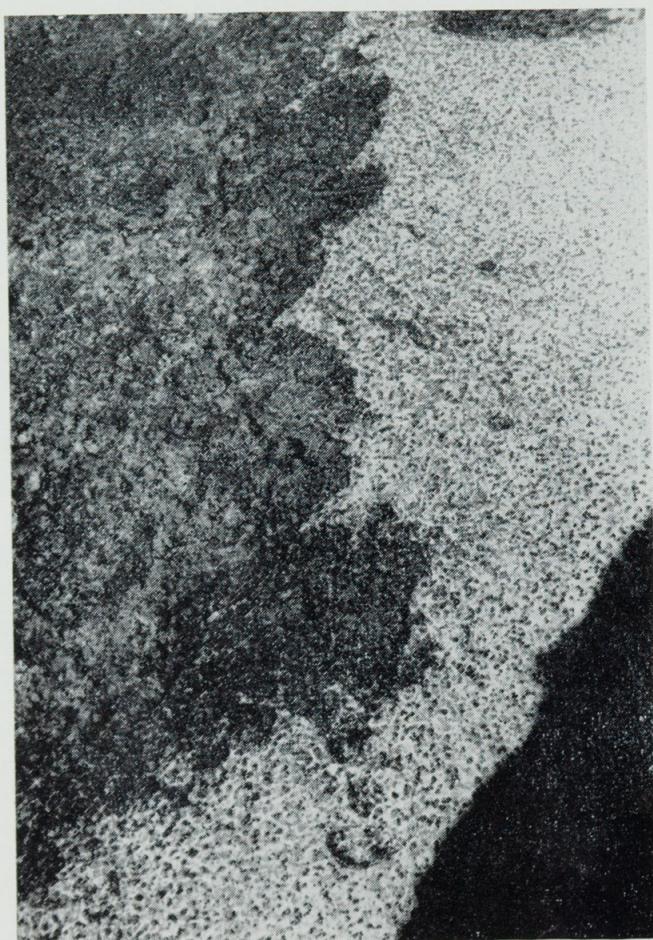
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1.—Intertidal limestone platform, Cape Vlaming, Rottnest Island. *Patelloida alticostata* dominant here before "catastrophe" of January 1959.



2.—Limestone platform with coralline algal association on left, *P. alticostata* alone on right (black at bottom right is shadow).

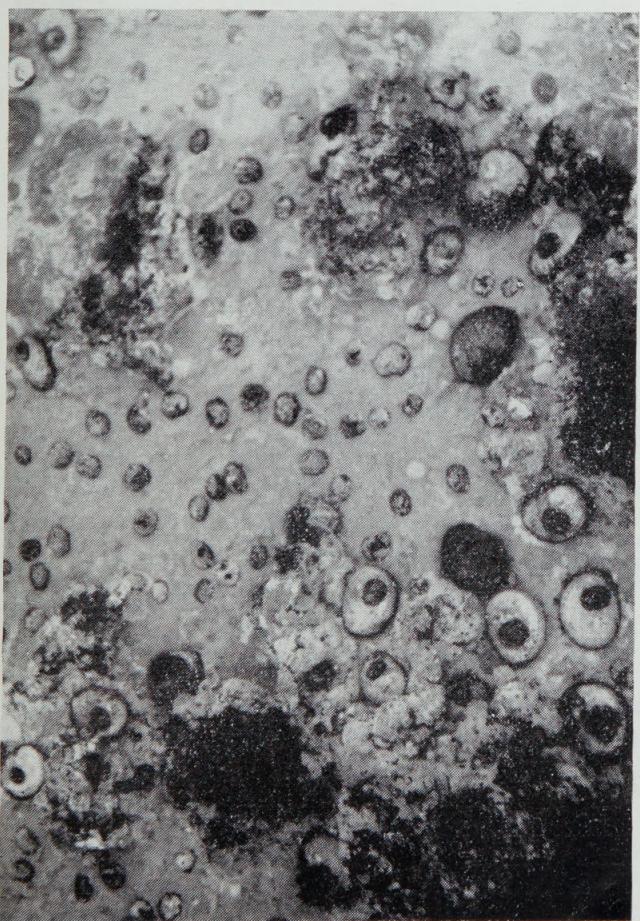


3.—Intertidal basalt rock (Mauritius) with *Colobocentrotus* on thin lithothamnion across centre; blue-green alga above.

PLATE I



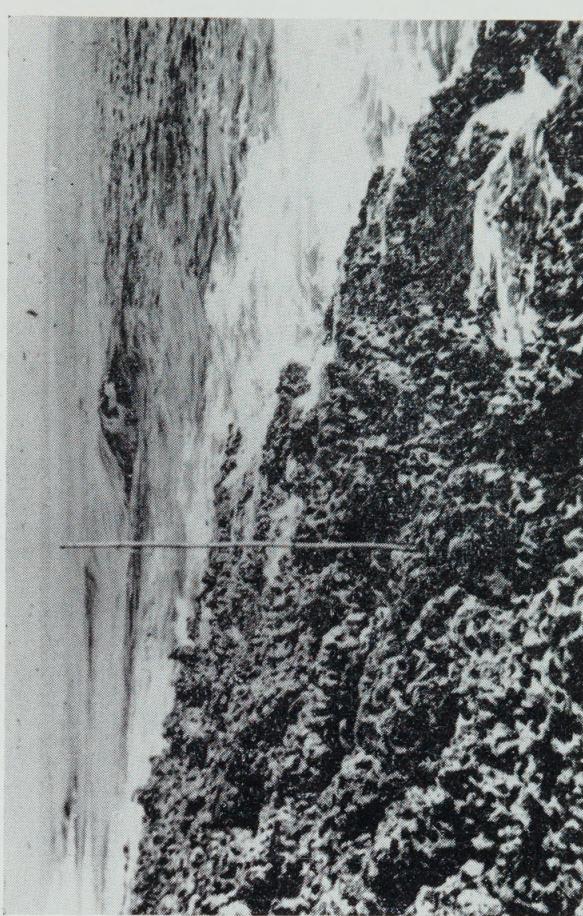
1.—*Haliotis roei*, *P. alticostata*, and encrusting lithothamnion on outer part of limestone platform. Note two *Haliotis* are weed-covered, but others are bare and each carries a *Patelloida nigrosulcata*.



2.—Empty limpet "homes" on limestone above high water in summer. One *Siphonaria luzonica* and three *Notoacmea onychitis* survive.



3.—*Patellanax laticostata* in typical "garden" on limestone. The limpet is bare of weed, but carries a single, weed-covered *P. nigrosulcata*. *P. alticostata* at right.



4.—Basalt rocks of exposed shore at Mauritius showing sea urchin burrows. (Six foot pole).

PLATE II

5.—The Uranoscopidae of Western Australia (Pisces, Perciformes)

By G. F. Mees *

Manuscript received—16th February, 1960

Introduction

McCulloch (1929, p. 335–336) lists six species of Uranoscopidae for Australia and only one species, *Kathetostoma nigrofasciatum*, as occurring in Western Australia. Whitley (1948, p. 27), in the latest list of fishes found in this state, increased the number of species recorded from Western Australia to two, *Kathetostoma nigrofasciatum*, and *Ichthyscopus sannio* (*I. sannio* is the species referred to in earlier literature as *Ichthyscopus lebeck* or *I. inerme*, cf. Whitley, 1936, p. 45).

It came as a surprise to me, and is an additional proof of the general poverty of ichthyological knowledge of this state, that I found in the collection of the Western Australian Museum and among material recently received, not less than six species of stonelifters and stargazers from Western Australia, of which three will here be described as new.

I would have liked to present a revision of the whole family of the Uranoscopidae, but for two reasons found this impractical. The first is that revisional work on a group of almost world-wide distribution can only with great difficulty be carried out in a somewhat isolated museum with a small collection and limited library facilities. The second is that many species of Uranoscopidae are very rare in collections, or are even known from their type specimens only. Obviously it would be difficult to receive these specimens on loan or to add anything essential to their original descriptions.

On the other hand, the detached description of a few supposedly new species, without mention of their nearest relatives—something that, unfortunately, has only too frequently been done—is about the poorest possible contribution to ichthyology, and rather adds to the burden of the future reviser than helps him. Therefore, I have taken a middle course: I have, from available literature, constructed a key to all the genera of Uranoscopidae, and a key to the species of the genus *Ichthyscopus*. As far as I can judge, with the exception of the large genus *Uranoscopus*, which probably will be found to harbour much nomenclatural weed among its many described species, the genera and species of the family differ from each other by clear-cut characters which have been well-described, so that perhaps there is no real need of a thorough revision. A revision of the genus *Ichthyscopus*, however, is necessary.

A description of the family characters is out of place in this short review, but I want to comment on one point. Though the velum behind the dentition of the lower jaw is usually well

developed, none of the Australian species has it with a filament. The only species with such a filament which I examined personally, is *Uranoscopus scaber* Linnaeus from the Mediterranean.

It is a pleasure to acknowledge my indebtedness to my colleagues Dr. M. Boeseman (Rijksmuseum van Natuurlijke Historie, Leiden), Mr. A. C. Wheeler (British Museum (Natural History), London), and Mr. G. P. Whitley (Australian Museum, Sydney), who gave much useful information on material under their care, and to the directors of the Australian Museum, Sydney, and the National Museum of Victoria, Melbourne, for the loan of specimens.

Key to the Genera of Uranoscopidae

1. a. Humeral spine exposed or obsolete
b. Humeral spine entirely concealed in a protruding dermal flap which is fringed below *Ichthyscopus*
2. a. Two dorsal fins, sometimes connected at base, the first with spiny rays
b. One dorsal fin, with soft rays only 6
3. a. D IX-II.8, A II.8, spines of first dorsal short, reduced to a series of immovable tubercles
b. D III to V, 13 to 15; A 13 to 15 *Pleuroscopus*
4. a. Barbel on chin
b. No barbel on chin 5
5. a. Head above only covered with a transverse bony plate, whence proceeds a Y-shaped apophysis which sends a limb to each orbit *Astroscopus*
b. Upper surface of head behind eyes entirely encased *Uranoscopus*
6. a. Body naked
b. Body scaly 9
7. a. D 12, A 17
b. D 13 to 18, A 13 to 18, in one species D 10 or 11, A 11 or 12, angle of praaeperculum rounded, not protruding *Kathetostoma*
8. a. Angle of praaeperculum with a short blunt spine
b. Angle of praaeperculum developed as a long flattened wing-like appendage, without spine, its length approximately 2.9 in head *Execestides*
9. a. D 13 to 20, A 17 or 18, barbel on chin
b. D 12 to 14, A 16 to 18, no barbel on chin *Genyagnus*
..... *Gnathagnus*

Synopsis of the Genera

(Synonyms are marked with a dagger †)

Uranoscopus Linnaeus (1758, p. 250)—type by monotypy *Uranoscopus scaber* L. Many species in nearly all tropical and subtropical seas.

Ichthyscopus Swainson (1839, p. 131, 269) (often written *Ichthyoskopus*, an emendation by Agassiz)—type by subsequent selection by Gill (1861), *Uranoscopus inerme* Cuvier & Valenciennes = *Uranoscopus Le Beck* Bloch & Schneider. Five species: *I. lebeck* (Bloch & Schneider, 1801); *I. fasciatus* Haysom (1957), *I. spinosus* n.sp., *I. insperatus* n.sp., *I. barbatus* n.sp.

*Western Australian Museum, Perth, Western Australia

Astroscopus "Brevoort" Gill (1860, before March 21, p. 20)—type by monotypy *Uranoscopus anoplos* Cuvier & Valenciennes (1831) = *Uranoscopus y-graecum* Cuvier & Valenciennes (1829, p. 229), cf. Jordan & Evermann (1898) and Jordan, Evermann & Clark (1930). Four species: *A. y-graecum* (Cuvier & Valenciennes), *A. guttatus* Abbott (1860, p. 365), *A. sexspinosis* (Steindachner, 1876, p. 167 pl. XIII Fig. 1) and *A. zephyreus* Gilbert & Starks in Gilbert (1897, p. 453, pl. LIV and LIII Fig. 2).

†*Agnus* Günther (1860, after June 1, p. 229)—type by monotypy *Uranoscopus anoplos* Cuvier & Valenciennes (1831, p. 493) = *Uranoscopus y-graecum* Cuvier & Valenciennes (1829), therefore a synonym of *Astroscopus*.

†*Anema* Günther (1860, p. 230)—based on *Uranoscopus monopterygius* Bloch & Schneider (1801), *Uranoscopus elongatus* Temminck & Schlegel (1843) and *Uranoscopus Le Beck* Bloch & Schneider (1801). These three species are now considered to belong to three different genera. Gill (1861) placed *Anema* partly in the synonymy of *Ichthyscopus* partly in that of his new genus *Genyagnus*, whereas under his *Gnathagnus* he forgot to quote Günther, though he did so under the only species included in that genus. It is certainly not an elegant way to dispose of a name, but as both Gill's later names have generally been accepted, and in order to avoid changes, I select *Uranoscopus lebeck* Bloch & Schneider as type species of *Anema*, which makes the name a synonym of *Ichthyscopus*.

Kathetostoma Günther (1860, p. 231)—type by monotypy *Uranoscopus Laevis* Bloch & Schneider (1801, p. 47). Seven species: *K. laeve* (Bloch & Schneider), *K. fluviatilis* Hutton (1872, p. 24), *K. giganteum* Haast (1873, p. 274), *K. averruncus* Jordan & Bollman (1889, p. 163), *K. alboguttata* Bean (1892, p. 121), *K. nigrofasciatum* Waite & McCulloch (1915, p. 469), *K. ornatus* Wade (1946, p. 215).

Nematagnus Gill (1861, p. 113)—type by monotypy *Uranoscopus filibarbis* Cuvier & Valenciennes (1829, p. 307). One species: *N. filibarbis* (Cuvier & Valenciennes). The presence of a barbel on the chin in this species in my opinion hardly justifies its generic separation from *Uranoscopus*, with which it seems to agree in all other respects. According to de Beaufort (1951, p. 49) *N. filibarbis* has been insufficiently described. The type specimen should be re-examined and its status, with that of the genus based upon it, reconsidered in the light of modern knowledge.

†*Upselonphorus* Gill (1861, p. 113)—based on *Uranoscopus y-graecum* Cuvier & Valenciennes (1829, p. 229) and *Astroscopus guttatus* Abbott (1860, p. 365). As type Kirsch (1889) selected *U. y-graecum*, which makes this genus a synonym of *Astroscopus*. This name has also been written *Epsilonophorus* (Kirsch 1889, p. 259) and *Upsilonophorus* (Kirsch 1889, p. 262-264).

Genyagnus Gill (1861, p. 115)—type by monotypy *Uranoscopus monopterygius* Bloch & Schneider (1801, p. 49). One species: *G. monopterygius* (Bloch & Schneider).

Gnathagnus Gill (1861, p. 115)—type by monotypy *Uranoscopus elongatus* Temminck & Schlegel (1843, p. 28). Three species: *G. elongatus* (Temminck & Schlegel), *G. innotabilis* Waite (1904a, p. 238), *G. laticeps* (Longley & Hildebrand 1940, p. 264), cf. Myers, 1946. *Gnathagnoides innotabilis grandior* Whitley & Phillipps (1939, p. 225) described on the basis of the sole character of growing to a larger size than *Gnathagnus innotabilis* must evidently be considered a synonym until more convincing arguments for its separation may be brought forward.

†*Synnema* Haast (1873, p. 274)—type by original designation and monotypy *Uranoscopus monopterygius* Bloch & Schneider (1801, p. 49), hence a synonym of *Genyagnus* Gill, 1861.

†*Hypselophorus*. This name appears nowhere but in the Zoological Record (O'Shaughnessy 1878, p. 19), apparently as an emendation of *Upselonphorus*.

Ariscopus Jordan & Snyder (1902, p. 479)—type by monotypy *A. iburius* Jordan & Snyder. One species: *A. iburius* Jordan & Snyder (1902, p. 479).

Execestides Jordan & Thompson (1905, p. 253)—type by original designation and monotypy *E. egregius* Jordan & Thompson. One species: *E. egregius* Jordan & Thompson (1905, p. 253).

†*Zalescopus* Jordan & Hubbs (1925, p. 312)—type by original designation *Zalescopus tosae* Jordan & Hubbs. For reasons given in the discussion of *Uranoscopus cognatus*, as described by Jordan & Hubbs, too slight to be of generic value and would reduce *Zalescopus* to a synonym of *Uranoscopus* with the consequence that the two species described in *Zalescopus* must now be known as *U. tosae* (Jordan & Hubbs) and *U. satsumae* (Jordan & Hubbs).

Pleuroscopus Barnard (1927a, p. 67)—type by original designation and monotypy *P. pseudodorsalis* Barnard. One species: *P. pseudodorsalis* Barnard (1927a, p. 67).

†*Gnathagnoides* Whitley & Phillipps (1939, p. 235)—type by original designation *Gnathagnus innotabilis* Waite. The differences between *G. innotabilis* and the type species of *Gnathagnus* as pointed out by Whitley & Phillipps, in my opinion are much too slight to justify generic separation.

†*Benthoscopus* Longley & Hildebrand (1940, p. 264)—type by monotypy *B. laticeps* Longley & Hildebrand. Myers (1946) has shown that the type species belongs to the genus *Gnathagnus* with which its authors did not compare it.

Genus *Ichthyscopus* Swainson

This genus, as here defined, includes all species with a fringed humeral appendage and strongly fringed hind border of the opercle. The members of the genus also agree in having the lower

border of the praaepercle flexible, covered with skin, and without spines or other projections. The heads are heavy and entirely encased in bone, but without spiny projections anywhere. Dorsal and anal fins long, D with 17 to 20 soft rays, A with 15 to 18 soft rays. Lateral line high, closely following the dorsal fin. In the species examined both lips are fringed with fairly long barbels though on the upper lip these fringes are present in the middle only, not on the sides; in *Ichthyscopus fasciatus* these barbels seem well developed on the lower lip only; in all representatives of other genera these barbels, if present, are much smaller and more or less rudimentary.

In other characters, there is a remarkable diversity between the various species: a first, spiny, dorsal fin may be present or absent, the body may be scaled or naked, barbels on the chin may be present or absent. These differences are of a nature and magnitude which elsewhere in the family have been considered to be of generic value. To me, however, the most important fact is that, notwithstanding the apparently considerable differences, the general appearance of the diverse species is very much the same. So great is their general similarity that, in my opinion, obscuring their evident affinity by dividing them in several genera, would only do harm. To this comes the additional argument that even now the genus embraces five species only, so that from the practical viewpoint it is undesirable to chop off a few monotypic genera. Unfortunately the classification of fishes is more seriously oversplit at the generic and family levels than almost any other group of animals. It has even been seriously contemplated to propose a uninomial system as: "the logical outcome of the tendency towards monotypic genera" (Hubbs 1943). Apart from the fact that my memory is quite unable to bear the burden of the hundreds of new generic names annually coined for familiar species and species which would be equally well placed in existing genera, this oversplitting, by obscuring true affinities, is contrary to the purpose of binary classification. Hubbs, quoted above, is perfectly right about the uninomial system, but

it is the tendency towards monotypic genera which is so absurd, not the binary system that has proved its usefulness over a period of two centuries. The genus, to all intents and purposes, is a collective unit to indicate not diversity but affinity. Perhaps it is a state of mind, whether one wants to stress similarities or differences. I am perfectly aware that these arguments are neither new nor original, they have been repeated many times by workers in many fields of zoology. However, when reading the works of several contemporary leading ichthyologists, I cannot help feeling that it is not a superfluous luxury to raise the point again and again.

It is most remarkable that to a genus of which for over 150 years only one species had been known, during the last two years four species could be added, all well-characterized.

The genus is known from the seas of India, China, Japan, and Australia.

Key to the species of *Ichthyscopus*

(The figures (counts of rays and scales) have been taken from material personally examined; the actual range of variation may be greater).

1. a. Body scaled 2
b. Body naked *I. insperatus*
2. a. No barbels on chin 3
b. Two small barbels on chin, body more or less uniformly pale brownish or (small specimens) with two broad dark crossbars *I. barbatus*
3. a. D II.17, A 17, dorsal spines rather weak, partly embedded in skin, upper surface dark, grey or blackish, boldly marked with white blotches of varying shape 4
b. D III-17, A 17, the anterior spiny part of the dorsal fin is only at its base narrowly connected with the soft dorsal; body spotted *I. spinosus*
- c. D 20, A 18, no spiny rays in D, which is continuous and not notched, body with six transverse bands *I. fasciatus*
4. a. Posterior nostril roundish (Fig. 5b) *I. lebeck sannio*
b. Posterior nostril an elongated slit *I. lebeck lebeck*

Ichthyscopus spinosus species nova

Differential diagnosis. Differs from all other species of the genus by the presence of a well developed spiny dorsal fin and by its remarkable colour pattern with small dots all over the body.

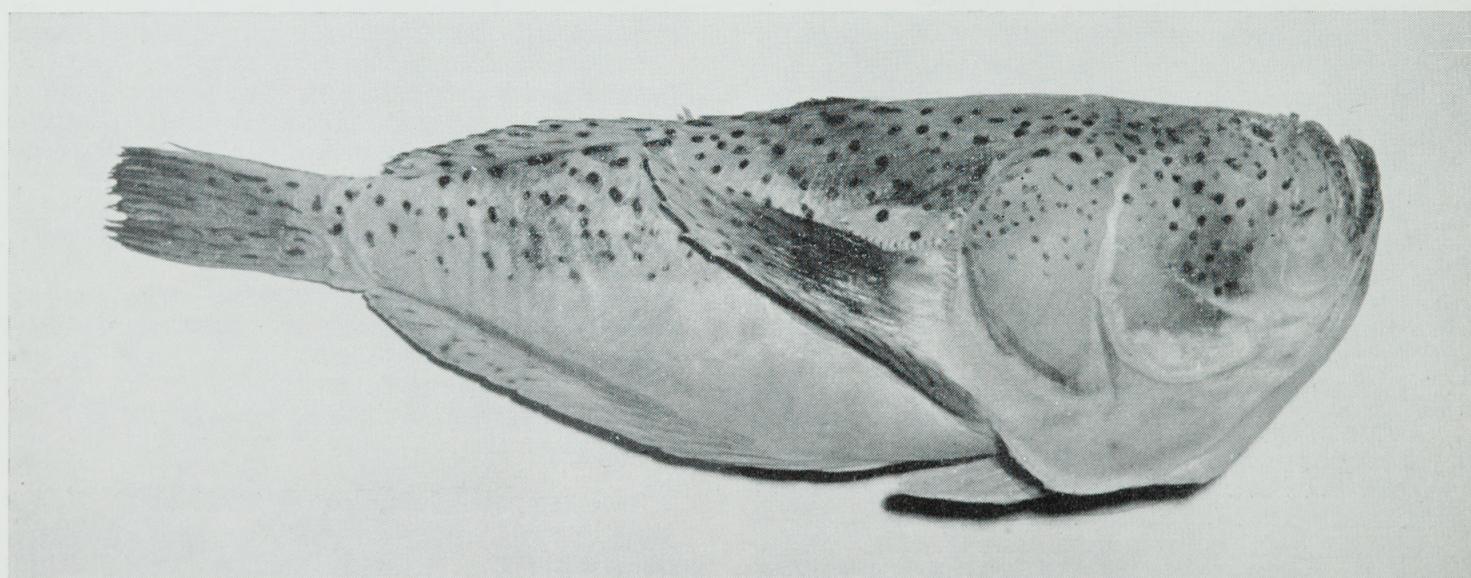


Fig. 1.—*Ichthyscopus spinosus* sp. nov., type, from right, ca. 2/5 × nat. size.

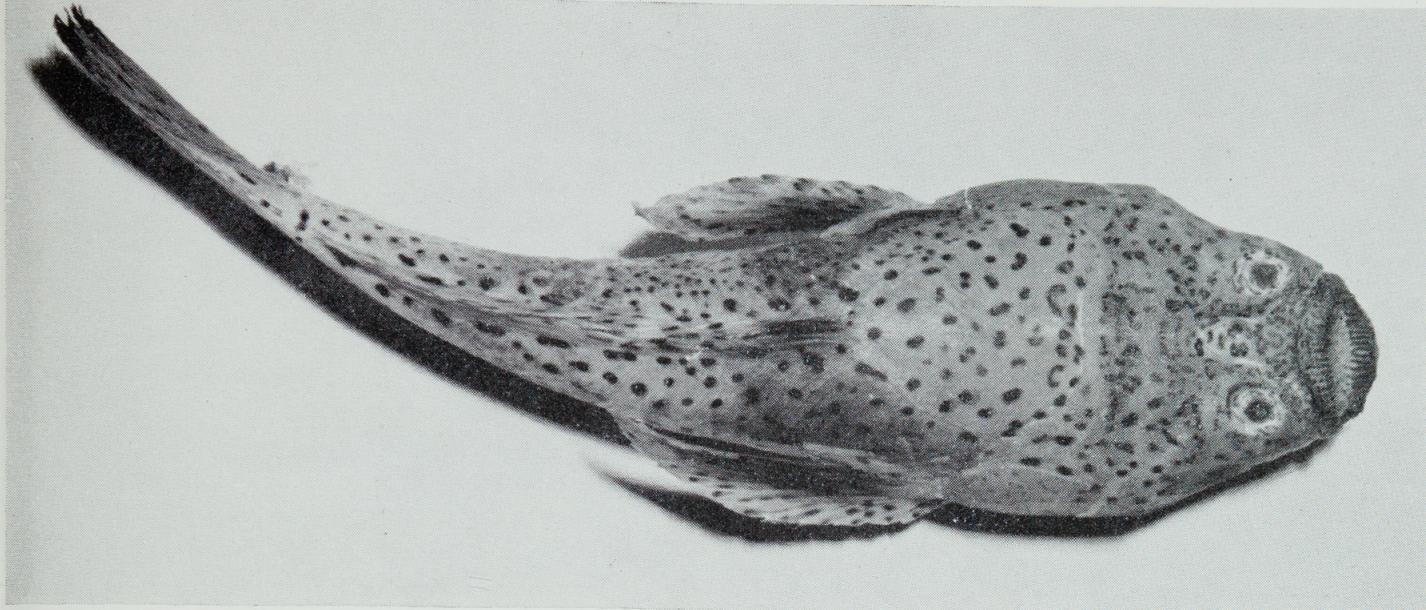


Fig. 2.—*Ichthyscopus spinosus* sp. nov., type, from above, ca. 2/5 × nat. size.

Type and unique specimen, described below, collected near Broome, N.W. Australia, received from the W.A. Fisheries Department on February 19th 1954 and presumably caught not long before. W.A.M. regd. no. P 3639.

Description. Figs. 1 and 2 give at a glance a general impression of the species and are, in my opinion, worth more than a lengthy description. The following notes are complementary to the figures.

D III.17, A 17, C with 10 divided rays and 2 developed undivided rays, P 16, V 1.5 spine concealed in skin, scales to caudal about 50 rows. Total length 330 mm, standard length 258 mm, length of D at base 116½ mm, length of A at base 126 mm, length of head from tip of mandible to hind border of opercle 107 mm, greatest width of head 78 mm, greatest depth of body (from D 1 to anal opening) 90 mm, width of mouth from side to side 31 mm, height of mouth (mandible) 32 mm, length interorbital sinus 24 mm, of bony armour behind 26 mm, distance between orbits 20½ mm, length of orbits 14 mm, nostrils close together in front of the orbits, the anterior nostril surrounded by a fringe, the posterior larger one with fringe along its anterior border only, the posterior border being formed by the orbit. Scales somewhat rudimentary, embedded in skin; breast, a great part of the belly, and the nape between the posterior border of the head armature the lateral lines and the origin of D naked.

Colours of preserved specimen. The ground colour is pale creamy, slightly tinged pinkish on the under surface and round the mouth; the whole upper half of the body including D2, P and C is dotted with dark brown spots, the majority of which are roundish, but on the neck some are rodshaped or boomerang shaped and between the eyes they are of various curly shapes. V unspotted, posterior half of A with brown spots, but less dark and well-defined than those of the back. D 1 entirely blackish brown. An ill-defined brownish area on the cheek, another above the humeral appendage, gradually

becoming paler in the direction of D 1; an ill-defined dark brown band over P, dark at the upper part of these fins, traces of a brownish half band below the middle of the soft dorsal.

***Ichthyscopus fasciatus* Haysom**

Ichthyscopus fasciatus Haysom, 1957, p. 139
Fig. 1—Cleveland Bay, near Townsville, North Queensland.

Differential diagnosis. Distinguished from other species of the genus by the presence of six dark and very distinct transverse bands on the body, combined with the presence of scales.

This species was described and figured well, and is evidently quite distinct. The figure more or less suggests the presence of a humeral spine, but in the description mention is made of: "A fringed humeral appendage, which hardly projects beyond the pectoral axil".

Material. I have not seen material of this species, which is known only from the type, a specimen of 102 mm in standard length trawled in Cleveland Bay and preserved in the collection of the Department of Harbours and Marine, Brisbane.

***Ichthyscopus barbatus* species nova**

Ichthyscopus sannio; Whitley, 1945, p. 42
(South-west Australia); Whitley, 1948, p. 27
(S.W. Western Australia).

Differential diagnosis. In general appearance close to *Ichthyscopus lebeck*, but differs by its plain coloration, shape of the operculum and interorbital groove for the reception of the maxillary processes, the presence of two small barbels on the chin, the simple or nearly simple, unbranched tentacles round the mouth, and larger scales.

Distribution. Only known from the western coast of South-West Australia between Dunsborough and Rottnest Island.

Type: W.A.M. regd. no. 4338.

Description. See Figs. 3 and 4, from which a general idea of the shape may be obtained.

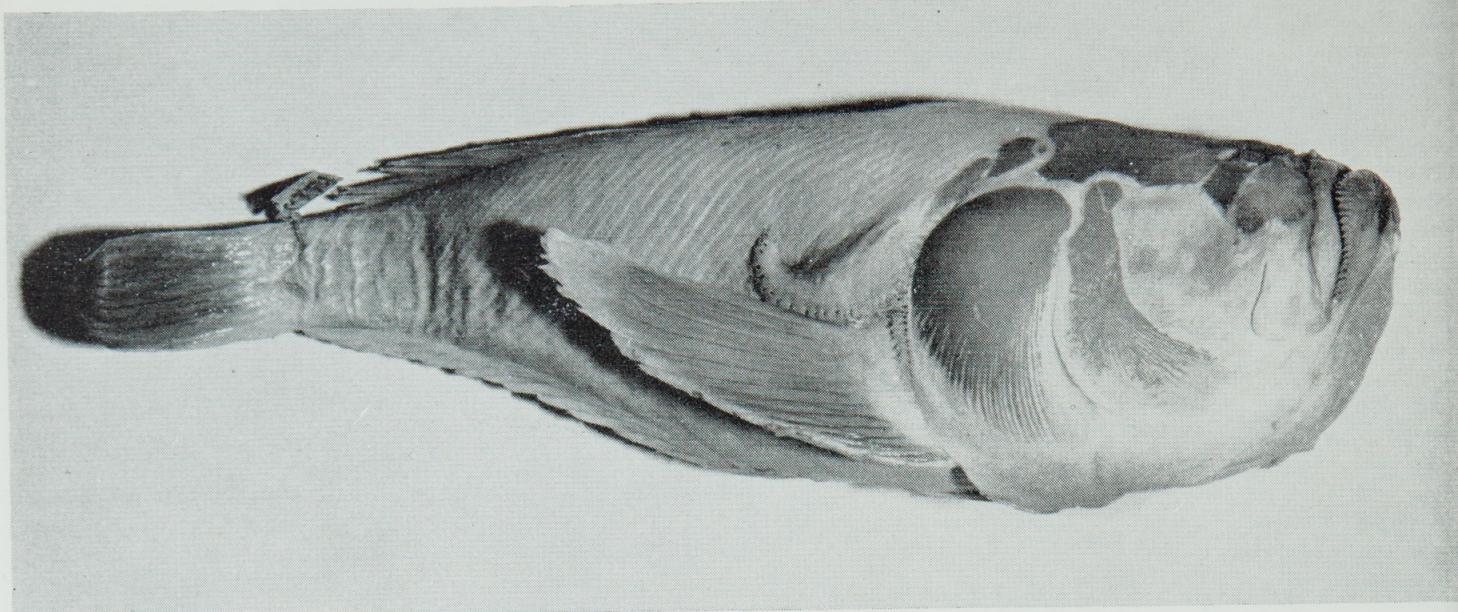


Fig. 3.—*Ichthyscopus barbatus* sp. nov., W.A.M. no. P 3438, from right, ca. 2/5 × nat. size.

D 19 (in large specimens the anterior two or three dorsal rays may be somewhat hardened, but they are never spiny), A 15-16, C with 10 divided rays, P 14, V I.5 with spine concealed in skin, scales in 36 to 44 rows (the exact number of rows of scales is somewhat difficult to count, as a number of rows branch at various places).

The head and sculpture of the head show a general similarity to *I. lebeck*, but differ as follows (Fig. 5a): two small barbels are always present, one above the other, on the middle of the chin, the lower of these being the larger; the tentacles surrounding the mouth are undivided or practically so, the fringes round the nostrils are less well developed, the naked space between the eyes for the reception of the maxillary processes is square behind, the operculum is more strongly curved antero-dorsally than postero-dorsally, the postero-ventral border of the maxillary makes about a right angle.

Colours of fresh specimen (P 4424). Upper parts pale brown, under surface pinkish (white, somewhat transparent skin with red blood shining through), exposed bony parts of head

brownish red, soft part of cheeks smoky brown, an ill-defined brown band from across the humeral appendage to the first five rays of the dorsal fin, and a second band underneath the posterior 7 rays of the dorsal fin and to base of caudal fin; sides of caudal peduncle with a blackish brown spot of the size of a farthing; D light brown, blackish brown at the outer edge; A whitish, somewhat reddish pink from blood; C black, P dull brown with whitish base, V pinkish white.

Colours of preserved specimens. All the ruddy tinge has gone, not only from the under surface but also from the head, so that only brownish and white remain. Small specimens are evidently more distinctly coloured. The two specimens of lot P 4431, notwithstanding the fact that they had been kept in formalin for 4½ years before I first examined them, still show dark cheeks, a dark tail, and two rather well-defined dark bands on the back. The anterior of these includes the posterior part of the humeral appendage and the first three dorsal rays, the posterior is under the 13th to the 17th

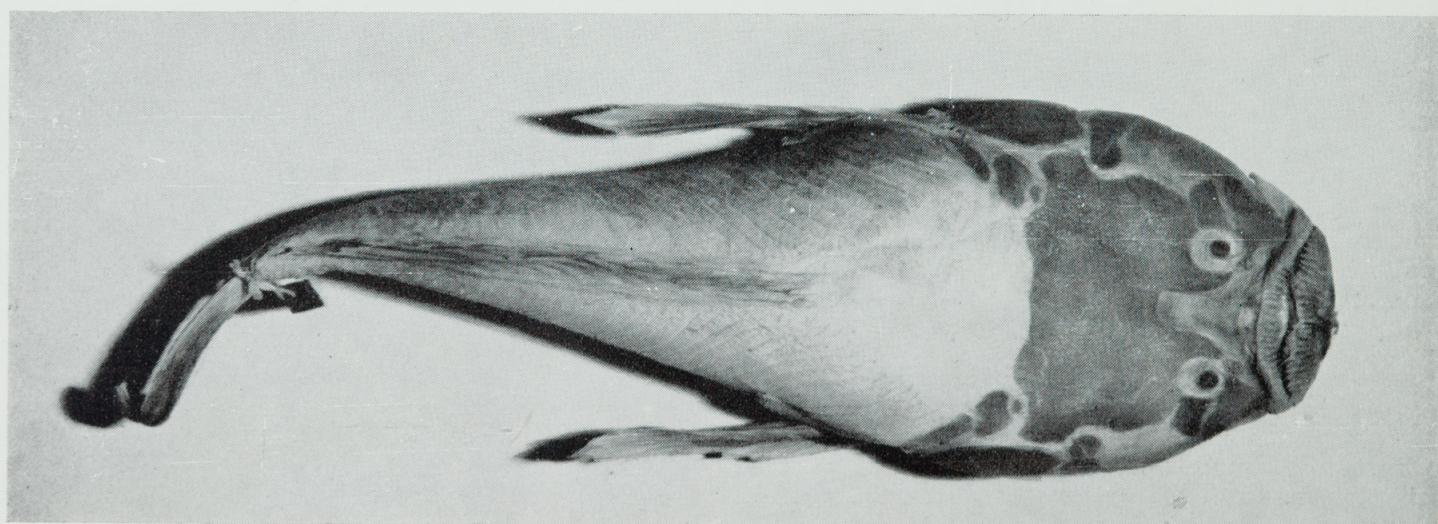


Fig. 4.—*Ichthyscopus barbatus* sp. nov., W.A.M. no. P 3488, from above, ca. 2/5 × nat. size.

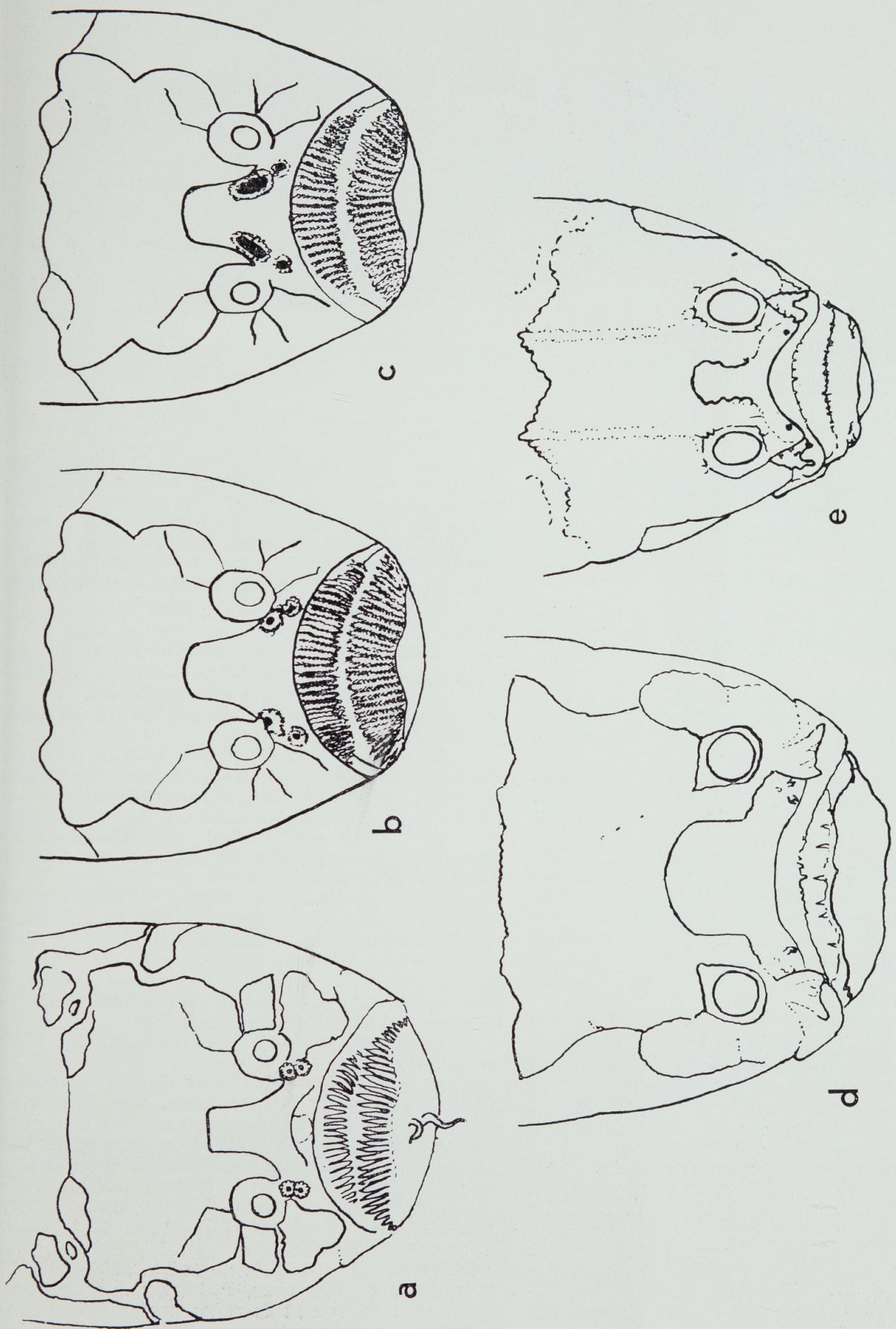


Fig. 5

- (a) *Ichthyscopus barbatus* sp. nov., head from above.
- (b) *Ichthyscopus lebeck sannio* Whitley, head from above.
- (c) *Ichthyscopus lebeck lebeck* (Bloch & Schneider), head from above.
- (d) *Kathetostoma laeve* (Bloch & Schneider), head from above.
- (e) *Kathetostoma nigrofasciatum* Waite & McCulloch, head from above.

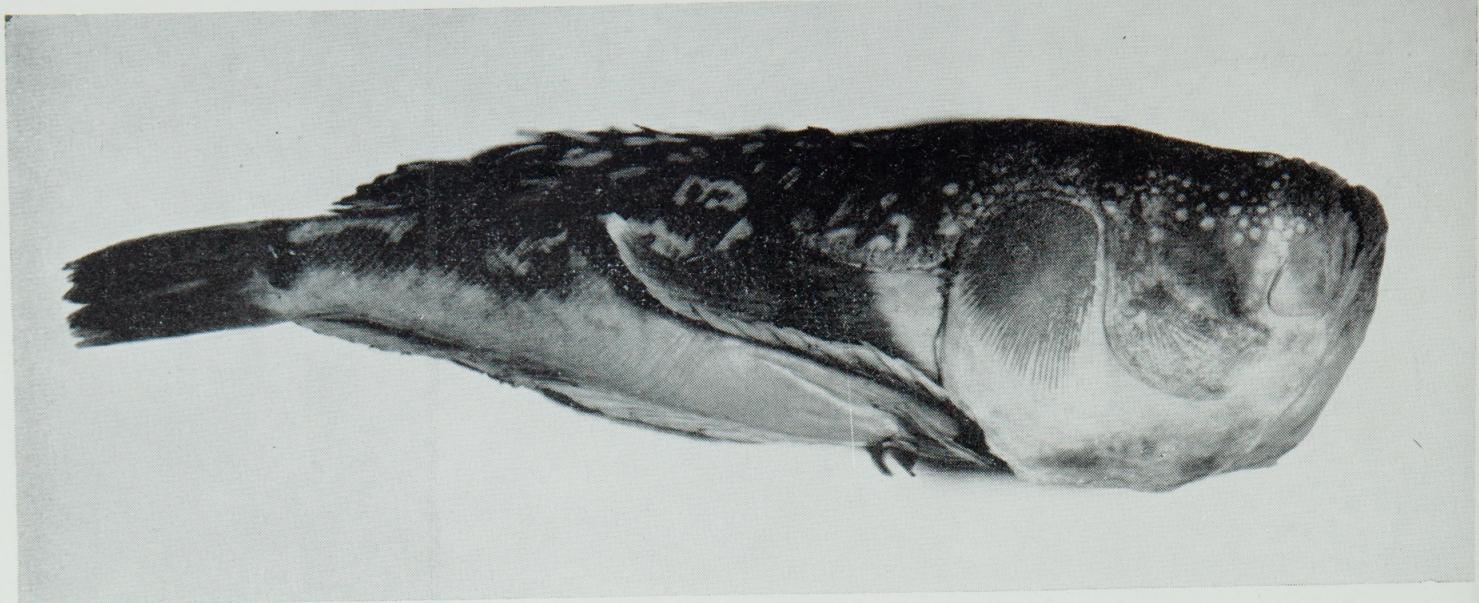


Fig. 6.—*Ichthyscopus lebeck sannio* Whitley, Aust. Mus. no. I.B. 2152, from right, ca. 7/20 × nat. siz.

dorsal ray; they are dark (blackish in the smaller specimen, somewhat paler in the larger specimen), very distinct on the back, and fading out down the sides, the anterior one above the base of the pectoral fin, the posterior one lower down.

Material. Seven specimens in the W.A. Museum.

P 672 Woodman's Point, received from fish-market Fremantle, 19.XI.1919, total length 25 cm, standard length 20 cm, D 19, A 16, L.l.±44.

P 1296 Busselton, received from Mr. A. J. Smith, registered on 27.V.1933, total length 187 mm, standard length 147 mm, D 19, A 16, L.l.±36

P 3488 Dunsborough, received from Mr. Alan Poole, registered on 9.II.1952, total length 40 cm, standard length 32.5 cm, D 19, A 16, L.l.±41.

P 4338 Between Rottnest Island and the Stragglers, collected by Mr. G. Turner on 22.X.1958, total length 41 cm, standard length 34 cm, D 19, A 16½, L.l. 37.

P 4424 Eagle Bay, collected by Mr. L. Beaman on 2.IV.1959, total length 375 mm, standard length 300 mm, D 19, A 15, L.l.±43. Weight 1245 g.

P 4431 (two specimens) Rottnest Island, collected by C.S.I.R.O. on 14.XI.1954, total length 130, 157 mm, standard length 105, 124 mm, D 19, 19, A 16½, 16, L.l. 37 and 38.

Habits, etc. Only on the two most recent specimens some information was received: specimen P 4338 was caught on a line with meat bait in 25 to 30 ft of water, specimen P 4424 was caught on prawn bait in about 9 ft of water on sand bottom near a reef at about 15 hrs. In the fresh specimen, and even more so when it was first captured, as Mr. Beaman told me, the eyes protrude, and actually stick out like hornlets on top of the head. In preserved specimens the eyes fall back and hardly suggest the curious position they have in life.

Discussion. Whitley (1945, 1948) identified the specimens of this species in the Western Australian Museum as *Ichthyscopus sannio* and

originally, judging from descriptions, this led me to believe that *barbatus* would only be subspecifically distinct, but actual comparison between specimens from eastern and western Australia showed such a number of differences as enumerated above, that I have no hesitation in describing it as a full species though it is obviously not too distantly related to *I. lebeck*.

Ichthyscopus lebeck sannio Whitley

Ichthyscopus sannio Whitley, 1936, p. 45—Patonga, Broken Bay, New South Wales.

Ichthycephalus inermis; Waite, 1899, p. 28 (New South Wales).

Ichthyscopus inermis; Waite, 1899, p. 112 (off the coast of New South Wales: many localities); Borodin, 1932, p. 96 (Southport, Queensland).

Anema inerme; Waite, 1904b, p. 50 (New South Wales); (pt.) Stead, 1906, p. 206 (Eastern Australia: specimen mentioned from Pelican Island, Brisbane Water, N.S.W.).

Ichthyscopus lebeck; Ogilby, 1918, p. 105 (Tewantin, Qld.); McCulloch, 1922, p. 102 (New South Wales); (pt.) McCulloch, 1929, p. 335 (New South Wales); Munro, 1945, p. 147-148 Fig. 6 (mouth of Noosa River, Qld.); Ogilby & Marshall, 1954, p. 84, 85 note (off the coasts of Queensland and New South Wales).

Ichthyscopus lebeck; (pt.) de Beaufort, 1951, p. 50 (Australia).

Differential diagnosis. The dark grey colour with the bold white markings, the somewhat rudimentary first dorsal fin, and the branched tentacles at the mouth, serve to distinguish this species from the other members of the genus.

Distribution. Seas of China, Japan, and eastern Australia, where known from Bowen (Queensland) down to Wollongong and Nowra (New South Wales).

Description. See Figs. 6 and 7. D II.17, A 17, C with 10 divided rays, P 16, V 1.5 with spine short and concealed in skin; scales 50-54 rows.

This form is fairly close to *I. barbatus*, but differs from that species by the presence of dorsal spines, the smaller scales, the very different coloration, the absence of barbels on the

chin, the strongly branched almost bushlike tentacles surrounding the mouth, the more developed fringes round the nostrils, the posteriorly rounded unarmoured space between the eyes, the dorsally evenly rounded opercles, and the sharper posterio-ventral angle of the maxillary.

Colours of preserved specimens. Generally dark brown, mottled with white above, and whitish below. Unencased parts of head, including chin, and whole nuchal area brown to greyish brown, with innumerable round whitish dots of various sizes; moreover the whole upper surface of the head, including the bony parts, and the nuchal region to half way along the dorsal fin, have a great number of tiny purely black spots. The white dots mentioned above gradually increase in size backwards, and change smoothly into the pattern of the back, which is dark brown variegated with large white blotches of various and varying shape. Fringes round mouth and nostrils, and at opercles and humeral appendages, dirty pinkish, D 1 blackish, D 2 as dorsal surface dark brown with white blotches, C dark brownish, posteriorly more blackish, P blackish brown with pale lower edge, V and A colourless.

Material. Two specimens received on loan from the Australian Museum, Sydney, from the coast of New South Wales, total length 283, 430 mm, standard length 227, 354 mm.

Discussion. Whitley (1936) described this form, as a species, on the basis of the following argument: "The Stargazer recorded from Australia as *Ichthyscopus lebeck* or as its synonym *inermis*, has been identified as such with reservations. As specimens have accumulated, it has become more obvious that our form represents a hitherto unnamed species which differs from figures of the Indian type mainly in coloration, but also in shape and proportions. A Malabar example of the true *I. lebeck*, from Dr. Francis Day's collection, differs from all my Australian ones in having the preocular fringes extending backwards halfway along each side of the interorbital depression, whereas Australian specimens have the fringes restricted to the anterior part only; they also have the opercles and vertex

less granulated than the Indian one, and there are slight variations in fin-rays and teeth".

The "slight variations of fin-rays and teeth" without mention of the nature of these variations is, to put it mildly, not very helpful, and as regards coloration, I find that specimens of *sannio* agree quite well with Day's (1878) description and plate of a specimen from Canara (Kanara of recent maps). The character of the shape of the posterior nostril seems to hold, however, as set forth below, so that I do not follow Munro (1945) who synonymised *sannio* with *lebeck*. Both Bloch & Schneider (1801) and Cuvier & Valenciennes (1829) described and depicted *lebeck* as a fish with an elongated posterior nostril. Mr. Wheeler examined the material of the British Museum (Natural History) for me, and I quote his comments (given in litt., 27.I.1959):

"We have three specimens from China (400, 317, 225 mm standard length), one from Bellinger River estuary, N.S. Wales (225 mm) and two from Madras (185, 71 mm). All the specimens have fringes round the nostrils, but in the Chinese and the Australian specimens the second nostril is round or slightly oval, while in the Indian material the nostril is elongate. The fringe of this nostril extends in consequence between the eyes and ends level with the posterior edge of the eye".

A sketch of an Indian specimen drawn by Mr. Wheeler served as the basis for Fig. 5c.

A specimen from Japan in the Leiden Museum, examined by Dr. Boeseman, has a round posterior nostril.

Unless a future closer examination reveals more distinguishing characters, the only point of difference between *lebeck* and *sannio* appears to be the shape of the posterior nostril. As this character seems to be quite constant, it deserves nomenclatural recognition, though I consider it much too slight for specific distinction. Therefore I recognise *sannio* as a geographical race of *lebeck*, with the distribution Japan, China and eastern coast of Australia, whereas the nominate race is apparently confined to India and Ceylon.

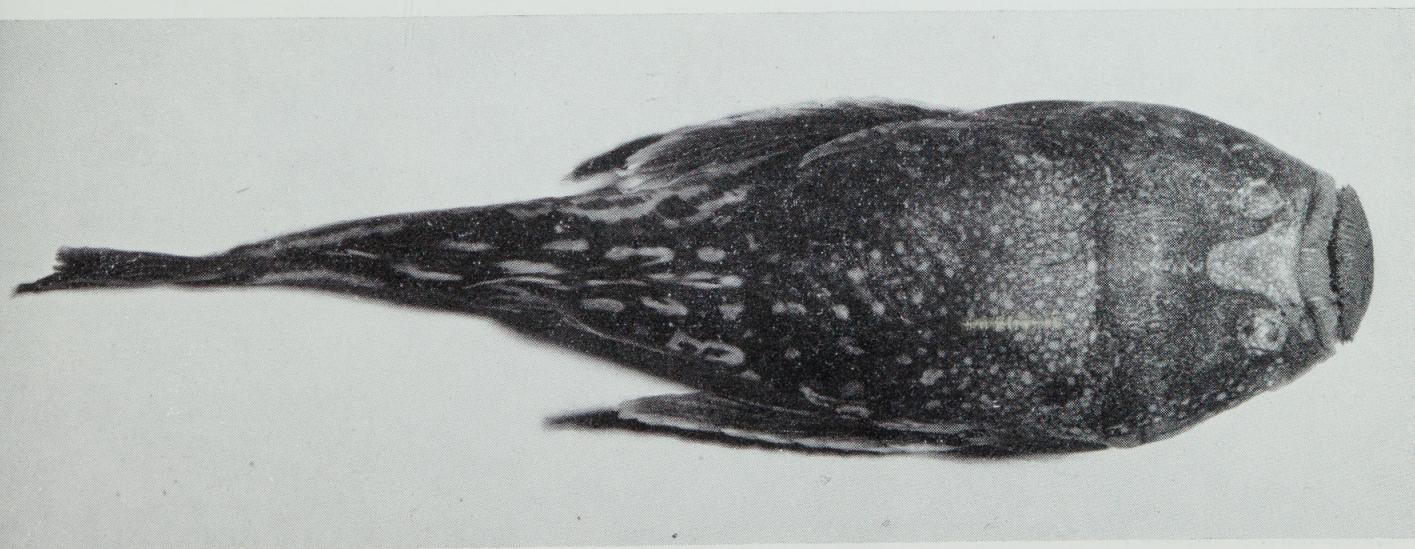


Fig. 7.—*Ichthyscopus lebeck sannio* Whitley, Aust. Mus. no. 2152, from above ca. 7/20 × nat. size.

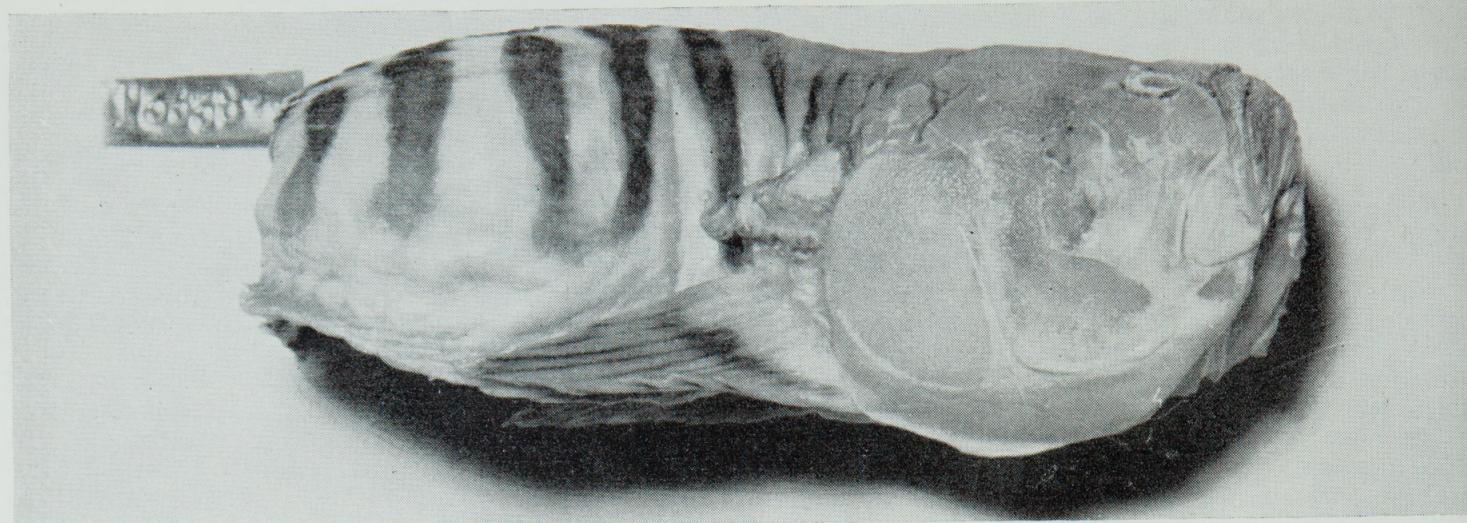


Fig. 8.—*Ichthyscopus insperatus* sp. nov. type, from right, ca. 7/10 × nat. size.

Ichthyscopus lebeck lebeck (Bloch & Schneider)

Uranoscopus lebeck Bloch & Schneider, 1801, p. 47—Tranquebar, India (reference copied).

Differential diagnosis. Differs from *sannio* and for that matter from all other species of the genus, by the shape of its posterior nostril, which is not roundish, but an elongated slit (Fig. 5c).

Material. None.

Discussion. Particulars on this race have been given in the discussion of *I. lebeck sannio*.

Ichthyscopus insperatus species nova

Differential diagnosis. Strikingly differs from the other species of the genus by the absence of scales, and by its very distinct colour pattern, with twelve vertical dark bands on body and tail (Figs. 8 and 9).

Type and unique specimen collected in Roebuck Bay, N.W. Australia, received from the W.A. Fisheries Department on February 15th 1954, and presumably caught not long before. W.A.M. regd. no. P 3638.

Description. D 17, A 17, C with 10 divided rays, P. left 13, right 14, V 1.5, spine small and concealed in skin. Total length about 215 mm, standard length about 170 mm (the specimen is curled up as the photographs show, and notwithstanding prolonged soaking in water it proved impossible to relax it), length of head from tip of mandible to hind border of opercle 63 mm, greatest width of head 55 mm, greatest depth of body (from anterior part of D to anus) 52 mm, width of mouth from side to side 24 mm, height of mouth (mandible) 19 mm, length of naked space between eyes $12\frac{1}{2}$ mm, of bony armour behind 23 mm, distance between orbits



Fig. 9.—*Ichthyscopus insperatus* sp. nov., type, from above, ca. 7/10 × nat. size.

13 mm, length of orbits $8\frac{1}{2}$ mm, nostrils small, close together, roundish, in front of eyes, both, but particularly the anterior one, surrounded by small fringes. Bony upper surface of head with a somewhat reticulated appearance, as is well shown in Fig. 9. Hind border of opercle and humeral appendage fringed, D with soft rays only, continuous, without notch, C rounded, P long, pointed, 4th ray longest.

Colours of preserved specimen. Pale brown above, darkest on the nuchal region, almost colourless below, with twelve dark brown crossbands which are dark on the back and gradually fade away two-thirds down the flanks towards the belly. These bands are darkest at the edges, and the three anterior bands actually consist each of a double band as their central parts are quite as pale as the remainder of the surface of the body in that region. The bands are situated as follows: the first from the anterior part of the humeral appendage over the nuchal region; the second from the middle of the humeral appendage over the nuchal region, passing well in front of origin of D; the third includes the membrane between the first and the second dorsal ray, and goes from there downwards and slightly backwards; the fourth includes the third and the fourth dorsal ray, and leads downwards where it fuses with the third band; the fifth includes the tip of the fifth, and sixth, and the basal portion of the seventh dorsal ray, tapering downwards where it closely approaches the sixth band; the sixth leads from the bases of the 9th and the 10th dorsal rays, tapering downwards (the tips of the two rays involved are also dark brown, but their middle parts are colourless); the seventh goes from the 12th and 13th dorsal ray downwards; the eighth goes from the 15th, 16th and 17th dorsal ray downwards; the ninth goes from the back of the caudal peduncle downwards; the tenth, eleventh and twelfth are on the rays of the tail at equal distances. Moreover the tips of the caudal rays are blackish brown, and its posterior part D has a subterminal blackish brown band on its rays; P is crossed by two indistinct brownish bands.

Interorbital sinus white and brown vermiculated, fringes of the lips pale pinkish brown with white spots.

Discussion. The reasons for including this scaleless species in the genus *Ichthyscopus* have been given on a previous page.

Genus *Kathetostoma* Günther

A well-defined genus characterised by the naked body, a strong humeral spine, and a spineless dorsal fin; D and A usually short. D 10-18, A 11-18. The number of rays is not given in the original description of *K. alboguttata* (Bean 1892), but according to Jordan & Evermann (1898, p. 2312) it is D 10, A 12, whereas Barbour (1941) found D 11, A 11. It is difficult to understand why Jordan & Evermann conclude their essay on the species with the remark "1 specimen known" as Bean in the original description records six specimens and they themselves noted "different specimens" a few lines earlier! Barbour (1941) commented upon this, but drew the wrong conclusion, as is evident from his reference

to the "unique type", whereas actually there were six co-types. Though I have not examined material of the species I find it difficult to believe that the seas round Cuba would be inhabited by a subspecies different from that occurring in the Gulf of Mexico, as Barbour claimed.

The genus is known from southern Australia (two species), New Zealand (two species), Pacific coast of tropical America (two species), and the Gulf of Mexico (one species).

Only the Australian species concern us here: both occur off the Western Australian coast and are represented in our collection; they can be separated as follows:

1. a. D 15-16, A 14-15 $\frac{1}{2}$, orbit posterio-medially pointed (Fig. 5d) *K. laeve*
- b. D 13-14, A 13-14, orbit roundish (Fig. 5e) *K. nigrofasciatum*

Kathetostoma laeve (Bloch & Schneider)

Uranoscopus laevis Bloch & Schneider, 1801, p. 47, pl. VIII—New Holland = New South Wales (reference copied).

Ichthyscopus laevis; Swainson, 1839, p. 269 (reference copied).

Kathetostoma laeve; Günther, 1860, p. 231 (Port Arthur, Tasmania); de Castelnau, 1872, p. 91 (rather common on the Melbourne market); Macleay, 1880, p. 562 (Tasmania, Melbourne); Macleay, 1881, p. 197 (Tasmania, Melbourne); Johnston, 1883, p. 115 (Tasmania, northern coasts); Tenison-Woods, 1883, p. 192 (Melbourne); Johnston, 1891, p. 33 (Tasmania); Waite, 1899, p. 113 (Port Jackson); Waite, 1904b, p. 50 (New South Wales); Stead, 1906, p. 206-207, pl. VIII (Victoria, Tasmania, New South Wales); Waite, 1911, p. 242 (Australia); Waite & McCulloch, 1915, p. 469-471 (New South Wales, Victoria, Tasmania; Investigator Group, South Australia); Waite, 1921, p. 140 Fig. 219 (no locality mentioned = South Australia); McCulloch, 1922, p. 102 (no locality mentioned = New South Wales); Waite, 1923, p. 163, Fig. (South Australia); (pt.) McCulloch, 1929, p. 335 (Victoria, New South Wales, Tasmania); Mees, 1959, p. 9 (Esperance, W.A.).

Cathetostoma laeve; Gill, 1861, p. 114 (Australian seas).

Differential diagnosis. D 15-16, A 14-15 $\frac{1}{2}$; a very convenient character to distinguish this species from the following is the shape of the orbits and sculpture of the bony armour on the dorsal surface of the head; this difference was already noted and illustrated by Waite & McCulloch (1915) but to assist ready identification I give sketches of both.

Distribution. Coasts of New South Wales, Victoria, Tasmania, South Australia (off the Investigator Group, South Australia, cf. Waite & McCulloch, 1915, p. 471), and Western Australia (recently recorded by me for the first time, cf. Mees, 1959). McCulloch (1929, p. 335) apparently overlooked the occurrence in South Australia as published by Waite and himself but included New Zealand in the range. Probably this record is based on Hutton (1872, p. 23), whose *K. laeve* was placed in the synonymy of *K. giganteum* (a species not yet described at the time) by Phillipps (1927) and others. A con-

venient difference between the two species seems to be the larger number of dorsal and anal rays in *K. giganteum*, and the fin-ray formula given by Hutton for his *K. laeve*: D 16-17, A 17-18 is very high for that species and fits *K. giganteum*. Admittedly Haast (1873) described *K. giganteum* as having D 16, A 14, but Waite (1911) on re-examination of the type specimen found that its actual formula was D 18, A 17 or 18. From the fact that Hutton (l.c.) gave a range of variation for D and A whereas he clearly stated to have but a single specimen, it is evident that the figures presented were copied from literature and not taken from his specimen. Günther's (1860) count for *K. laeve* is also high (D 17, A 17), higher than one would expect for that species, and if this count correctly represents the fin-ray formula of his specimens, they are likely to belong to *K. giganteum*, a species not yet described at the time, and not to *K. laeve*. Anyway, for the moment I feel justified in accepting Phillipps's identification and exclude New Zealand from the range of the species. It may be remarked that Hutton's (1890, 1896) identification of *K. giganteum* with *K. laeve*, which probably caused the confusion, was not accepted by subsequent revisers (Waite & McCulloch 1915), and Hutton (1896, p. 315) himself already suggested that *giganteum* might be a valid species.

Material. Two specimens in the Western Australian Museum.

P 1745 Esperance, received from Mr. P. F. Sullivan, registered on 7.IV.1937, total length 322 mm, standard length 265 mm, D 15, A 15.

P 3629 Esperance Bay, received from Dr. K. Sheard, registered on 16.I.1954, total length 355 mm, standard length 290 mm, D 16 $\frac{1}{2}$, A 14 $\frac{1}{2}$ (15?).

Besides, there is in our collection an old mounted specimen from Tasmania (no precise locality or date).

Eight specimens received on loan from the National Museum of Victoria range from 225 to \pm 430 mm total length, 180 to \pm 370 mm standard length, D 15-16, A 15-15 $\frac{1}{2}$, except one specimen which has evidently been damaged in its youth and has D 11, though in front of D a few tubercles covered with skin are apparent.

Kathetostoma nigrofasciatum Waite & McCulloch

Kathetostoma nigrofasciatum Waite & McCulloch, 1915, p. 469, pl. XIII Fig. 1, 2—Doubtful Island Bay, South-western Australia, 20-25 fathoms.

Kathetostoma nigrofasciatum; Waite, 1921, p. 141, Fig. 220 (South Australia); Waite, 1923, p. 164, Fig. (South Australia); McCulloch, 1929, p. 335 (South Western Australia); Whitley, 1948, p. 27 (south coast of Western Australia).

Differential diagnosis. D 13-14, A 13-14; the differences between this species and *K. laeve* are given under that species and in the key.

Distribution. Known from the coasts of South Australia and the south coast of Western Australia.

Material. Three specimens in the Western Australian Museum.

P 710 Off Bald Island, received from Chief Inspector of Fisheries on 25.VIII.1920. Total length 238 mm, standard length 190 mm, D 14, A 13 $\frac{1}{2}$. P 1057 "South of Rottnest" ¹, W.A. Trawling Co. Ltd., registered in October 1929. Total length 260 mm, standard length 210 mm, D 14, A 14.

P 2317 Albany, received from Mr. R. C. Winterford, registered on 25.VIII.1941. Total length 21 $\frac{1}{2}$ cm, standard length 17 $\frac{1}{2}$ cm, D 14, A 14.

Genus **Uranoscopus** Linnaeus

This genus is characterized by a scaly body, strong humeral spine, two dorsal fins, either entirely separated or connected at their bases, of which the first is spiny, and by the head which is almost entirely encased in heavy bony armour, with spines along the lower edge of the praaeperculum.

The genus occurs in all tropical and subtropical seas in a fairly large number of species.

Two species have been recorded from Australia, but there is a possibility that these are identical.

Uranoscopus cognatus Cantor

Uranoscopus cognatus Cantor, 1849, p. 1003—Sea of Penang (reference copied).

Uranoscopus cognatus; Mees, 1959, p. 9 (Shark Bay).

Material. A single specimen of a *Uranoscopus* of which the characters agree with *Uranoscopus cognatus* as given by de Beaufort (1951).

P 4280 Trawled between Kok's Island (N. end Bernier Island) and Quobba Point (N. of Carnarvon), Shark's Bay, by "Bluefin", W. & W. Poole, 23-30 July 1958.

Description. The specimen mentioned above has an overall length of 183 mm, standard length 149 mm, depth of body 40 mm, breadth of head 54 mm, D III-13, A 13, lower border of praaeperculum with four spines, lower edge of suboperculum with one spine, scales in about 56 series, humeral spine well-developed, directed obliquely upwards and backwards; somewhat rudimentary fringes on the lips, rather better developed on the lower lip, hind border of opercles slightly fringed.

Colour of preserved specimen: brownish grey, somewhat freckled with light greyish on the nape. Body, C, and to a lesser extent P, with very small black spots. C and D greyish, D 1 black with the lower half of the first spine and its membrane white, and a small basal patch at the end below and behind the third ray white.

Discussion. Two specimens ascribed to *Uranoscopus terrae-reginae* Ogilby (1910) received on loan from the Australian Museum and

¹ This probably means that the company from which the specimen was received extended its operations all along the coast of Western Australia south of Rottnest Island, and that the specimen may have been captured anywhere along the south coast. Certainly there is no proof that it was collected near Rottnest or elsewhere along the west coast. The locality of provenance of the specimen, therefore, is uncertain.

coelonging to the original Endeavour material, compare very well with our specimen of *cognatus*, but for the differences described below. They measure 120 and 129 mm in standard length. The bony parts of the head in our specimen are somewhat more rugose, which is to be expected in a larger specimen, and they are entirely decolourized with the exception of the black on D 1 which has the same shape and extent as in our specimen; the general shape and pattern of the bony parts of the head, spines, and number of rows of scales agree, but whereas in our specimen the whole region on the back from nape to lateral lines is devoid of scales, in the two specimens of *terrae-reginae* this part of the back, with the exception of the nape just behind the bony armour, is covered with small scales, as already mentioned by Ogilby (1910).

I found it difficult to judge how important the character of the squamation of the nuchal area is and asked Mr. Whitley for information on the material retained in the Australian Museum, which includes a specimen recently caught off the coast of New South Wales. He replied as follows (in litt., 15.IX.1959): "With reference to *Uranoscopus terra reginae*. In 8 cotypes, 2 have the predorsal area naked but the rest have scales for about half or more than half the distance from origin of dorsal fin to parietals. The New South Wales specimen has naked nape and predorsal area. There are no spots on the heads or bodies of any of the specimens as in your specimen of *cognatus*."

Unless the type material consists of a mixed sample of two different species, it would seem that the character of the squamation of the nape varies within one species (perhaps small specimens have scales which may disappear with growth), whereas even in the specimens with scales on the nape, not the whole nuchal region is covered by them. In my opinion this is ample proof that the presence of scales on the nape cannot be used as a generic character, and therefore the genus *Zalescopus* becomes a synonym of *Uranoscopus*.

For the moment the status of *Uranoscopus terra reginae* must remain unsettled, for though the evidence put forward above is suggestive of the possibility that this name is a synonym of *U. cognatus*, the available material is insufficient to decide this with certainty. *Uranoscopus terra reginae* was hitherto only known from Queensland, but in August 1959 the Australian Museum received a small specimen from 72 fathoms, E. of Newcastle, N.S.W. Mr. Whitley (in litt., 10.VIII.1959) kindly allowed me to publish this record, and added a description of its colours in life, as taken by Dr. A. A. Racek:

Upper side bluish-grey, with occasional and irregular dark grey spots, widely interspaced. Projecting spines reddish brown. Ventral side light grey. Caudal fins with yellow tinge. Eyes light blue.

Concerning Ogilby's (1910) paper, in which the description of *Uranoscopus terra reginae* occurs, McCulloch (1914) made some interesting remarks. The only copies of this work ever dis-

tributed were apparently pre-issued author's re-prints. As Ogilby's paper has been quoted in the Zoological Record and has been used by later authors, it will be convenient to recognise it as having been published, though I do not think that it meets the requirements set forth by the International Commission on Zoological Nomenclature. If Ogilby's work is rejected, I shall probably become the unfortunate author of *U. terra reginae*, as previous records in literature (McCulloch 1914 and 1929) are nomina nuda *.

References

(works marked with an asterisk (*) have not been available to me)

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6.—The Physiography, Vegetation and Vertebrate Fauna of North Island, Houtman Abrolhos

By G. M. Storr*

Manuscript received—16th February 1960

Introduction

North Island ($28^{\circ} 18' S$, $113^{\circ} 35' E$), the most northern of the Houtman Abrolhos, was named by the officers of H.M.S. 'Beagle', who charted the adjacent seas towards the end of May, 1840. It is 11 miles distant to the N.W. from its nearest neighbours, the Wallabi Islands, which it more nearly resembles in size, shape and elevation than the low narrow islands of the Easter and Pelsart Groups. But probably owing to its remoteness, North Island has never been regarded geographically as one of the Wallabi Group.

Only four parties of naturalists have investigated North Island. The first was the visit of the 'Beagle', already referred to; its narrative was published by Commander J. L. Stokes 1846).

The Percy Sladen Trust Expedition, led by Prof. W. J. Dakin, spent a few days on the island in November, 1913. Dakin (1919) described, *inter alia*, the physiography of the island, and Alexander (1922) enumerated the vertebrates collected by the expedition.

North Island was next visited by Dr. D. L. Serventy on December 6, 1945. He did not publish an account of the trip, but his manuscript notes were made available to the writer.

Finally the island was examined from September 6-8, 1959, by a party from the Zoology Department of the University of Western Australia, comprising D. H. Edward, A. R. Main, H. Waring and the writer. We were accompanied by visiting English botanist, Dr. Mary E. Gillham. Our purpose was to study the vegetation (hitherto undescribed) and to collect or record the terrestrial fauna. This visit was made during an expedition to the Wallabi Islands to collect live wallabies for the Department's research program on the physiological ecology of marsupials.

Physiography

North Island is roughly oval in shape, has a maximum length of $1\frac{1}{4}$ miles and an approximate area of 450 acres. It consists of a low central plain surrounded by dunes of calcareous sand, the highest of which attain an elevation of 50 feet.

The limestone basement of the island seldom exceeds 5 feet above present sea-level, so that it outcrops on the central plain in only a few small areas. Other exposures are equally re-

stricted, viz. the low cliffs around South Point, the seaward toe of Record Hill and the walls of the sink-hole in the extreme south-western corner of the plain. It is the absence of extensive coralline limestone surfaces that is responsible for most of the differences in physiognomy and vegetation between North and the Wallabi Islands.

At present the highest dunes are Record Hill and Northwest Hill, both on the western side of the island. In 1913 Dakin considered the eastern dunes higher than the western. Since then, the eastern dunes have been severely blown out, their few remnants today being no higher than 20 feet. To ascertain the cause of this erosion, a questionnaire was circulated among Geraldton fishermen.

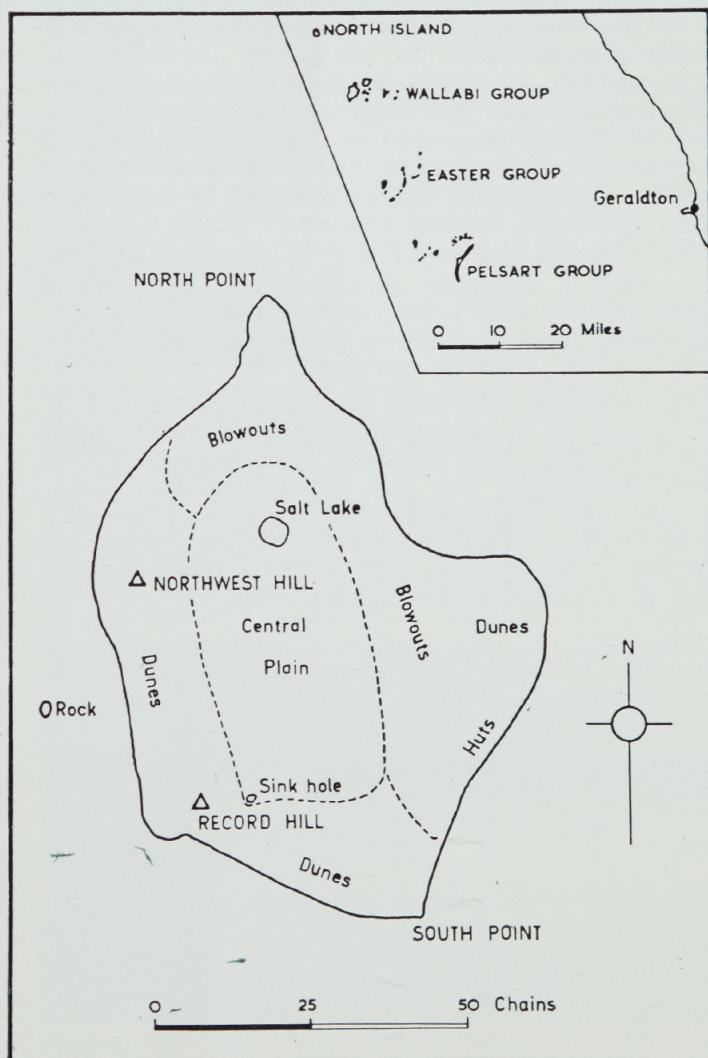


Fig. 1.—Map of North Island.

Messrs. A. Bertelsen and H. Akerstrom inform me that the vegetation which had hitherto covered the eastern dunes was destroyed by fire in October 1935, after which the sand began to drift. Denudation was apparently slow for many years, for in 1945 Serventy referred to erosion only in the south-eastern corner of the island. Soon after, however, another fire devastated this sector. According to Mr. G. C. Barker, the movement of sand accelerated about 1950, reaching a peak two years later. On his return to the island in February, 1952, he found the low scrub behind North Point engulfed in sand blown from the dunes to the south-east. Previously the far northern end of the island had been densely vegetated.

At present the blown-out areas show no sign of regeneration. The few remaining clumps of *Spinifex longifolius*, perched precariously on pinnacles of sand up to 8 feet high, are quite incapable of spreading. In view of the meagre rainfall and the persistence of strong southerlies in summer, it seems unlikely that this cycle of erosion will be arrested before the eastern and northern dunes are completely levelled.

Our outline of the island (Fig. 1) shows some minor discrepancies with that depicted on Admiralty Chart 1723. If these are in fact indicative of subsequent changes in the coastline, it would appear that North Point has grown since the original survey by the 'Beagle' and that a high-level beach has been formed by the filling in of the shallows along the south shore of the north-eastern bay.

In section the central plain is like a saucer. The soil around the higher rim is fairly deep and is largely composed of fragments of shells. Towards the centre it becomes shallow and loamy. In certain areas the soil is distinctly guano-like and contains bones of birds.

The sink-hole is a circular, steep-sided depression, with a diameter of about 10 yards and a depth of 3-4 feet below the surrounding plain. Its muddy floor was damp but contained no free water at the time of our visit.

The shallow salt-lake at the northern end of the plain is roughly circular and almost two acres in area. Its northern and eastern banks slope steeply for 2-3 feet down from the plain. It contained water during our visit but was dry in November, 1913. As its level is unaffected by the state of the tide, the water is probably replenished annually by winter rain.



Fig. 2.—From eastern dunes, looking south over a big blowout. Fishermen's huts in left middle distance.

Vegetation

The strand vegetation is dominated by *Spinifex longifolius* R. Br., *Salsola kali* Linn., *Atriplex cinerea* Poir and *Cakile maritima* Scop. Where backed by stable dunes the *Spinifex* soon gives way to *Atriplex paludosa* R. Br., *Scaevola crassifolia* Labill., *Olearia axillaris* (D.C.) F. Muell., *Myoporum insulare* R. Br. and *Exocarpus sparteus* R. Br. Where the dunes are unstable, *Spinifex* extends inland, but the bare floor of blowouts is colonised only by *Cakile*, though sparsely and quite ineffectively. In the lee of the big eastern blowouts *Nitraria schoberi* Linn. grows luxuriantly along with dense clumps of *Salsola* and *Myoporum*. Towards South Point where the sand is shallow over the limestone, the following calciphilous shrubs appear: *Pimelea microcephala* R. Br., *Spyridium globulosum* (Labill.) Benth. and *Acanthocarpus preissii* Lehm.



Fig. 3.—From northern dunes, looking southwest over central plain to Northwest Hill. *Atriplex paludosa* and *Scaevola crassifolia* in foreground.

The vegetation of the central plain varies with the nature and depth of the soil. Deep shelly soils around the rim support a low dense shrubbery of *Rhagodia baccata* Moq., *Atriplex paludosa* and *Threlkeldia diffusa* R. Br. At lower levels and with increasing clay content, the following species become dominant: *Frankenia pauciflora* D.C., *Limonium salicornaceum* F. Muell. and *Arthrocnemum arbuscula* (R. Br.) Moq., the last-named being replaced by *A. halocnemoides* Nees wherever limestone approaches the surface. The low-lying clayey soils south of the salt-lake are water-logged in winter; they carry a dense mat of *Salicornia blackiana* Ulbrich, *Sporobolus virginicus* (Linn.) Kunth. and *Suaeda australis* (R. Br.) Moq., the only closed community on the island.

Much of North Island is thus dominated by low chenopodiaceous shrubs. Apart from a few big bushes of *Nitraria*, the vegetation is everywhere below five, and for the greater part, below three feet high. The aspect of the vegetation varies seasonally. At the time of our visit winter annuals were very much in evidence. On the central plain in particular, the ground between shrubs was carpeted with herbage, among which grasses and composites were especially conspicuous.

Reptiles

Chelonia mydas (Linnaeus).—In December 1945, Serventy observed about a hundred Green Turtles in the north-eastern bay close to the

shore. He and his companions searched the beaches but found no egg-mounds. However, A. Bertelsen informs me that "in December and January, hundreds of turtles come to the north side of the island to lay their eggs". North Island would be the southernmost breeding station of the species in Western Australia. Whether they still breed there is unknown, but we found on the north-western beach the remains of a turtle whose carapace was about three feet long.

Python spilotes (Lacépède).—No living Carpet Snake has ever been observed on North Island by naturalists. Yet there is no doubt that they occur here or did so until recently. Three of my informants (Geraldton fishermen) have seen them, including G. C. Barker who has lived on North Island only since 1945; however, he believes their numbers to be "very few". We found an intact backbone of *Python* with numerous petrel remains on the floor of a blowout in the north-western sector of the island.

Heteronota bynoei Gray.—Nine specimens of this gecko, including a very young animal, were collected from under slabs of limestone on the central plain.

Phyllodactylus marmoratus (Gray).—Four specimens of this gecko were obtained from the same locality as the preceding species.

Amphibolurus barbatus (Cuvier).—Alexander found Jew Lizards "plentiful" in 1913; Serventy "saw a few" in 1945; and subsequently G. C. Barker has observed them. Our party found none during three days work all over the island.

Egernia kingii (Gray).—We saw few King Skinks and collected only one, a juvenile from beneath a slab of limestone.

Lygosoma (Sphenomorphus) lesueurii Duméril and Bibron.—Several were seen in the coastal *Spinifex*, but we were unable to catch them. Two mummified specimens were found that matched in all essentials with a series from West Wallabi Island. Another and smaller skink, possibly *Ablepharus lineo-ocellatus*, occurred in the *Spinifex* but likewise evaded capture.

Lygosoma (Rhodona) praepeditum Boulenger.—Two specimens of this small worm-like skink were found with geckoes under slabs of limestone.

Birds

The following list is restricted to land-birds. Marine and littoral species will be discussed elsewhere.

Turnix varia (Latham).—In 1840 Stokes found the central plain "covered with coarse grass, where a great many quails were flushed." Both Alexander and Serventy described the Painted Quail as "common". We found no trace of the species, which presumably became extinct some time after 1945.

Phaps elegans (Temminck).—Serventy failed to see the Brush Bronzewing in 1945; nor have we or any of our informants observed it. If Alexander was not in error when he recorded the species for North Island, it must have become extinct soon after his visit.

Falco cenchroides Vigors & Horsfield.—A single kestrel was seen by Alexander, who supposed that it was a visitor from the mainland.

Hirundo neoxena Gould.—At the time of our visit there were at least 20 Welcome Swallows on the island, mostly in the vicinity of the fishermen's huts. A nest under an eave contained yellow-gaped fledglings that were able to fly. Serventy did not observe this species. As the island entirely lacks natural nest-sites (cavernous limestone and undercut cliffs) swallows have probably become established only since the erection of the huts (according to G. C. Barker who built the first one in 1946, there were four by 1950; at present there are thirteen).

Cincloramphus cruralis (Vigors & Horsfield).—At least three singing males of the Brown Songlark were observed on the central plain.

Zosterops gouldi Bonaparte.—Silvereyes were largely confined to the few places, such as the leeward slopes of the eastern dunes, where the shrubbery (*Nitraria* and *Myoporum*) was relatively tall and dense.

Anthus novae-seelandiae (Gmelin).—Pipits were surprisingly more plentiful on beaches and in dunes than on the central plain. Since Serventy observed a few birds, and Alexander a pair, the species is probably resident, rather than a visitor from the mainland as suggested by Alexander.

Mammals

Macropus eugenii (Desmarest).—Since previous visitors had never recorded this species—Stokes (1846, pp. 162-4) being explicit as to its absence—our discovery of numerous Tammar remains was entirely unexpected. The bones, almost wholly mandibles, were only found in the bottom of blowouts, usually associated on the east side of the island with rabbit skulls, and on the north-west with petrel bones. They probably owed their preservation to the dry climate and the calcareous nature of the sand that had covered them.

In answer to my question, what do you know of wallabies on North Island, A. Bertelsen replied, "have seen wallabies there in 1928 to 1930, only one or two and much larger than on East or West Wallabies". F. C. Burton wrote, "Extinct. Put there by fishermen in the early days of fishing". My other informants had no knowledge of wallabies on the island.

Whether these remains are those of a long extinct natural population or of a recent introduction, can only be decided after carbon-dating of the bones. Meanwhile the first alternative seems more likely; for the fact that the skulls of most of the tammars had been lost indicates that the population was not contemporary with the rabbits, whose skulls have been preserved in great abundance.

Neophoca cinerea (Péron & Lesueur).—Seals have been seen on North Island by A. Bertelsen ("several times in January") and G. C. Barker ("a few").

Oryctolagus cuniculus (Linnaeus).—Eight rabbits, trapped at Geraldton, were released by A. Bertelsen in 1934. The introduction was successful, Serventy finding them "exceedingly numerous" eleven years later. G. C. Barker writes, "In 1945 there were quite a few. We had a few traps and often had a rabbit. It was usual when we arrived in February to see a

dozen or so around the camp at daylight. A walk across to the west side would show 20 or 30 rabbits. They did not appear to burrow but lived under bushes, and as their only enemy was the sea-eagle they continued to live that way. They now appear to be extinct. This year and last I did not notice any, and it would appear the two cats which have gone wild and live in the centre of the island have cleared them out."

Discussion

In the not very distant past North Island more nearly approached the Wallabi Islands in richness of fauna. Today its fauna can only be classed as depauperate. The dismal history of recent extinction may be divided into four periods.

(1) Before 1840.—Petrels, probably *Puffinus pacificus*, ceased for unknown reasons to breed on the island, despite its apparent ecological adequacy. It is also probable that a population of the wallaby, *Macropus eugenii* became extinct in this period, a period that is completely undocumented.

(2) 1840-1913.—Unfortunately Stokes' account is so brief that no decision can be made whether any animals became extinct in this period. No naturalists and apparently few fishermen visited the island in the 73-year period between the visit of the 'Beagle' and the Percy Sladen Trust Expedition.

(3) 1913-1945.—Between the two World Wars deep-sea fishermen from Geraldton were increasingly using the island as a haven in rough weather. As the island entirely lacks potable water and other resources useful to fishermen, landings were infrequent and unexploitative. To provide themselves with an emergency source of food, fishermen released on the island, wallabies and rabbits, only the latter becoming established. Early in the period the Brush Bronzewing seems to have become extinct. Fires in this period began the process of denudation that culminated in the next.

(4) After 1945.—The post-war establishment of the crayfishing industry has introduced new factors. The island is now inhabited by about 40 people for several months each year. Domestic cats have become feral, though there is no evidence that they breed. With man, there are now two efficient predators, more or less permanently living on the island.

Faunal impoverishment, movement of sand, and loss of vegetation have all accelerated in this period. The following species have either become extinct since 1945 or nearly so: Carpet Snake, Jew Lizard, Painted Quail and European Rabbit. While the disappearance of the rabbit is not regretted, it does illustrate how easily even a tenacious and abundant animal may be exterminated on a relatively small island. The recent establishment of a widespread species of swallow on North Island is little consolation for the loss of the other species.

Acknowledgments

The Director of Fisheries (Mr. A. J. Fraser) generously placed at our disposal free ship transport from Geraldton to the islands. Thanks are also expressed to those fishermen who gave information recounted in the text; to Dr. D. L. Serventy for the use of unpublished data; and to Mr. R. D. Royce for identifying our plant specimens.

The expedition was financed partly by a W.A. University Research Grant but chiefly by a generous grant from C.S.I.R.O. to Professor H. Waring for marsupial work.

I am indebted to Dr. Main, my supervisor, for overall direction and for reading the manuscript.

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7.—A Note on Two Small Mammals of the Darwin Area

By S. J. J. F. Davies *

Manuscript received—17th November, 1959

A trapping study of the small mammals at Humpty Doo, near Darwin, was carried out from 1956 to 1959. *Phascogale ingrami* was found in the pandanus fringe, the paper-bark fringe and the thorn scrub, while *Melomys cervinipes albiventer* was collected only in the pandanus fringe.

Both small mammals produced young in the wet season, and in *P. ingrami* breeding is probably limited to that period.

It appears that these two small mammals can maintain populations only in habitats where annual fires and floods do not occur.

Introduction

Between November 1956 and March 1959, I spent 15 months at Humpty Doo, on the Adelaide River, about 40 miles south-east of Darwin (131° 15' E; 12° 40' S) in connection with magpie goose studies. During that period I collected some data on the distribution and biology of two small mammals, a marsupial *Phascogale (Planigale) ingrami* (Thomas) and a rodent *Melomys cervinipes albiventer* (Kellogg).

Phascogale ingrami is a small, brown, shrew-like marsupial, one of the smallest of the dasyurids, remarkable for its greatly flattened skull. Its distribution is as yet incompletely known but it is probably restricted to the areas of Northern Australia influenced by the monsoons. Like the true Shrews, *Sorex*, it is actively predaceous, at least in captivity, capable of killing and consuming grasshoppers almost as large as itself.

Melomys cervinipes, a grey-brown Murid the size and shape of a large vole (e.g. *Clethrionomys* sp.), but with a tail as long as the body, is one of the smallest of the scaly-tailed, arboreal rats inhabiting the forests of the Malay Archipelago, New Guinea and Northern Australia.

As in some other Australasian Murids, e.g. *Pseudomys*, *Leggadina*, etc. (Ellerman 1941), there are only four mammae in *M. c. albiventer* females, concentrated at the anal end of the abdomen. The young mice each hold a teat continuously in their mouths until they are two to three weeks old and are dragged about, marsupial-like, by the mother as she moves. Jones (1925) describes a similar state of affairs in the related genus *Leporillus*. A number of races of the species have been recognized along the coast from northern New South Wales to west of Darwin, as well as a number of insular forms, but all previous material of *M. c. albiventer* has been collected at the type locality, Brooks Creek, about 120 miles south of Darwin. My specimens agree with the type description by Kellogg (1945) in every respect, and would,

therefore, extend the known range of the form to include the flood plain of the Adelaide River.

The animals were trapped in Oxford Longworth live traps, generally unbaited on account of the active ant fauna, but in localities expected to yield *M. c. albiventer* the traps were baited with domestic hen laying-pellets. The traps were set five yards apart in a straight line on the ground. Breakback traps, of both rat and mouse sizes, were set from time to time, but no catches were ever made in them.

Both species have been held for some time in captivity. A small *M. c. albiventer* colony has been established at the C.S.I.R.O. Wildlife Survey Section's headquarters in Canberra, but *P. ingrami* has been kept only in Darwin, where individuals have survived for a month on a diet of grasshoppers, raw meat and cod-liver oil. *M. c. albiventer* has been bred on a diet of rabbit food-pellets and green food.

The information collected is incomplete but it may be of interest in view of the present development of the area into irrigated rice farms, with which is associated a gross environmental change, and also because our knowledge of these small mammals still depends on the records of the early collectors, summarised in Troughton (1941).

B. J. Marlow of the Australian Museum, Sydney (where specimens of both animals have been deposited) has kindly checked the identification of both animals. I am grateful to J. Saxby and W. J. Mills for help in the field, and to F. N. Ratcliffe, J. H. Calaby, H. J. Frith and Dr. W. D. L. Ride for their comments on the manuscript.

Environment

Humpty Doo lies in the 60-inch rainfall belt. Most of the rain falls between November and March, the wet season, whereas the rest of the year is relatively dry, with grass fires burning through the drying vegetation in April and May almost every year. Day temperatures reach 90° to 100° F in the wet season and 70° to 80° F in the dry season; night temperatures are somewhat lower, falling below 60° F at times in the dry season.

The flood plain of the Adelaide River at Humpty Doo is sharply delimited from the higher ground that is not subject to inundation during the wet season. The vegetation of this higher ground is a tropical savannah woodland consisting of an open forest of *Eucalyptus* with a shrub layer of varying density. Most of the trapping was done in an area where the trees grew close together, the herb layer being pre-

1



2



PLATE I

- 1.—Pandanus fringe.
- 2.—Paperbark fringe.

sent only in the wet season and shrubs virtually absent.

At the junction of the flood plain and the savannah woodland there is typically a transition zone or fringe dominated, according to local conditions by *Pandanus* or *Melaleuca*. The pandanus fringe is an open association of *Pandanus* and grassland (see Plate I, 1). The paperbark fringe is likewise an open association, of *Melaleuca* and grassland, differing from the true paperbark forest in that a thick herb layer develops (see Plate I, 2).

In addition to savannah woodland, pandanus fringe and paperbark fringe, trapping was also carried out in a fourth habitat, thorn scrub, consisting of isolated patches of *Acacia* and other shrubs with thick undergrowth growing on higher ground in the open plain.

Results

Phascogale

In 1955-1956 H. J. Frith (personal communication) found a number of *P. ingrami* hiding under sacks on a rice levee bank that extended several hundred yards across the flood plain from the pandanus fringe. The plain was flooding rapidly at the time, and the animals had probably been forced by the rising water to leave the vegetation along the foot of the bank, where they had been living.

There are two records for 1956-57, both in February. A pair of *P. ingrami* was collected from under a log lying in thorn scrub, and a

single animal was seen at the base of a pandanus clump when it was chopped down late in the month.

The trapping programme carried out from September 1957 to March 1959 is shown in Table I. It should be noted that whereas in 1957-58 no two habitats were trapped simultaneously, in March 1959 simultaneous trapping was used to compare—

- (1) savannah woodland and pandanus fringe (1-18 March); and
- (2) savannah woodland and paperbark fringe (18-25 March.)

The captures during the two seasons are set out in Table II.

In 1957-58 seven *P. ingrami* were taken in both the pandanus and the paperbark fringes. Although none were trapped in thorn scrub, a single animal was observed there in January 1958. One of the specimens collected in pandanus fringe on March 3, 1958 had been reduced to a skeleton by ants before it was found, so it remained unsexed. Some of the females ate their litters shortly after being taken into captivity, and only two litter sizes were established immediately after capture, one of 12 and another of 8.

In addition to the captures made in March 1959 and presented in Table II, a female *P. ingrami* without a litter was found while undergrowth was being cleared in the pandanus fringe in August 1958 (J. Mills, personal communication.) The weights and measurements of some animals are given in Table III.

TABLE I
Trapping programme for small mammals at Humpty Doo, 1957-1959
Number of trap-nights per month

| Habitat | 1957 | | | 1958 | | | | 1959 | | Total |
|----------------------------|-------|------|------|-------|-------|-----|------------|-------------|-----|-------|
| | Sept. | Jan. | Feb. | March | April | May | March 1-18 | March 18-25 | | |
| Tropical savannah woodland | 63 | 63 | 0 | 0 | 0 | 0 | 90 | 35 | 251 | |
| Pandanus fringe | 0 | 0 | 126 | 63 | 63 | 189 | 108 | 0 | 549 | |
| Paperbark fringe | 63 | 63 | 126 | 63 | 0 | 126 | 0 | 35 | 476 | |
| Thorn scrub | 0 | 0 | 0 | 0 | 63 | 0 | 0 | 0 | 63 | |

TABLE II
Number of captures of *Phascogale ingrami* per month at Humpty Doo, 1957-1959

| Habitat | 1957 | | | | 1958 | | | | 1959 | | Total |
|----------------------------|-------|-------|--------------|--------------|-------|-------|--------------|-------------|------|---------------|-------|
| | Sept. | Jan. | Feb. | March | April | May | March 1-18 | March 18-25 | | | |
| Tropical savannah woodland | 0 | 0 | ... | ... | ... | ... | 0 | 0 | 0 | 0 | 0 |
| Pandanus fringe | ... | ... | 0 | 2f(L) 1 U | 0 | 1f(B) | 2f(L) 2 m | ... | ... | 5f 1 U 2 m | |
| Paperbark fringe | 0 | 1f(L) | 1f(L) 1 m | 0 | ... | 0 | ... | 1f(L) | ... | 3f 1m | |
| Thorn scrub | ... | ... | ... | ... | 0 | ... | ... | ... | ... | 0 | |

(L) = with pouch young or pregnant, (B) = without pouch young, f = female, m = male, U = unsexed.
NOTE.—A male was brought in by one of the farm cats on 4/1/58.

TABLE III

Quantitative data from some *Phascogale ingrami*
trapped at Humpty Doo, Darwin

| Date of capture | Sex | Details |
|-----------------|-----|--|
| 3/3/58 | F | Naked pouch young 0.5 cm long |
| 9/3/58 | F | Weight 4.5 g (including young): naked pouch young 1.0 cm long |
| 17/5/58 | F | Weight 5.0 g |
| 2/3/59 | M | Length 14.7 cm, tail 7.2 cm |
| | M | Length 15.6 cm, tail 7.2 cm: |
| 8/3/59 | F | Length 14.5 cm, tail 7.2 cm: 12 naked pouch young 0.55 cm long |
| 21/3/59 | F | Length 14.7 cm, tail 6.6 cm: 8 naked pouch young 0.8 cm long |

It can be seen that no *P. ingrami* has been taken in tropical savannah woodland despite 251 trap-nights' work there, while the rate is one animal per 68 trap-nights in the pandanus fringe, and one animal per 119 trap-nights in paperbark fringe. Apparently therefore, whereas *P. ingrami* is common in the pandanus fringe it is less so in the paperbark fringe and possibly absent in the tropical savannah woodland. Probably it cannot live on the flood plain, which is inundated often to a depth of several feet, for up to six months of the year, but sight records indicate that it occurs on the higher patches where thorn scrub grows.

The animals appear to enter traps most readily between January and March, the catch averaging one animal per 58 trap-nights in that period (excluding trapping in tropical savannah woodland) and one animal per 504 trap-nights at other times. Presumably the animals are most active in the wet months; certainly no litters have been collected outside that period, whereas every female obtained within it has been either pregnant or carrying a litter. The only litter born in captivity was dropped about January 26th, 1958.

Melomys

This species has been taken at only one locality—a pandanus fringe habitat on the west side of the Adelaide River. A male and a pregnant female were collected there in February 1958 during 126 trap-nights, and a single adult male during 63 trap-nights in May of the same year. A young male (length 29.3 cm, tail 15.0 cm) was taken during 108 trap-nights in March 1959. In addition a sight record of several *Melomys* was made, 20 miles away, in pandanus fringe on the east side of the Adelaide River, in late May 1958. Since *Melomys* is an arboreal animal these results are probably not a true reflection of the population density, but they do suggest that *M. c. albiventer* is more restricted to pandanus fringe than *P. ingrami* and that it breeds in the wet season. The pregnant female dropped her litter of three on February 20, 1958, in captivity. The young mice, when raised in Canberra, bred first at the age of seven months, but it is possible that they would have bred earlier had the weather been warmer. Their three litters contained 3, 2 and 3 young.

Discussion

As has been pointed out above, both small mammals appear to be confined to the marginal areas lying between the flood plain and the tropical savannah woodland, occurring also on the isolated spots of high ground on the plain. A consideration of certain major environmental factors suggests an explanation of this distribution. The plain is annually flooded, and since neither of the animals is aquatic it is reasonable to suppose that the annual inundation is sufficient to prevent a population from becoming permanently established there.

The patches of thorn scrub on high ground might be expected to be populated, since they are both dry and isolated from fire by the swamps. On the other hand, the tropical savannah woodland is annually burnt out at the end of the wet season by fires that consume the undergrowth, leaving the trees alone standing. Such fires would probably be sufficient to wipe out any population of small mammals in the woodland, and thus prevent their permanent establishment. Although both fires and floods do occasionally reach the pandanus and paperbark fringes, these areas have features that might be expected to minimise their effects. As can be seen in Plate I, 1, clumps of young pandanus grow around the bases of older trees in the pandanus fringe, and form large tough thickets. The paperbarks, on the other hand, tend to grow on ground so damp (e.g. on drainage lines) that the grass never dries sufficiently for fires to obtain a proper hold. Possibly, however, the lower catching rate of *P. ingrami* in paperbark as compared with pandanus fringe reflects the fact that if a fire does burn through the former very little shelter remains for the small mammals, whereas in the pandanus fringe the pandanus clumps provide fire-resistant shelters large enough to shield them from the heat of the fire.

The distribution patterns of *P. ingrami* and *M. c. albiventer* at Humpty Doo may, therefore, be examples of the same situation as that reported in some Finnish birds by Sammalisto (1957), where each of two major habitats is unsuitable for a species, but the marginal areas between them provide suitable conditions for it. It will be of great interest to see whether any measures for flood or fire control taken during the development of the area affect the distribution of these animals.

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Part 3

Kelvin Medallist, 1959: E. J. Underwood

In 1928, E. J. Underwood graduated with First Class Honours in the Faculty of Agriculture within the University of Western Australia. At the University of Cambridge he worked under Dr. H. E. Woddman and Professor T. B. Wood and obtained his Ph.D. in 1931. Between 1931 and 1945 he held the position of Animal Nutrition Officer at the Western Australian Department of Agriculture and was a part-time lecturer in the University of W.A. During this period he obtained world-wide recognition in scientific circles for his contributions to a number of animal nutrition and husbandry problems; these included the Denmark wasting disease, botulism in sheep, pregnancy toxæmia, and fat lamb production. The successful completion of these investigations not only had important local practical significance but added appreciably to basic scientific knowledge.

Between 1936 and 1938 Professor Underwood gained further overseas experience, through the award of a Commonwealth Fund Service Fellowship. He worked at the University of Wisconsin, U.S.A., on problems of mineral nutrition of animals and visited research centres throughout North America, the United Kingdom, and South Africa.

At the beginning of 1946 he was appointed Hackett Professor of Agriculture, Dean of the Faculty of Agriculture, and Director of the Institute of Agriculture at the University of Western Australia.

Over the last thirteen years Professor Underwood has been responsible for the organization and development of teaching and research at the Institute of Agriculture which has now one of the largest graduate research groups in any Australian University. A feature of this development has been the fine public and industrial support which has been secured. He has also acted as Chairman of a Government Committee on Agricultural Education and Extension in Western Australia, which presented practicable short-term and desirable long-term plans for the development of an effective system of agricultural education and extension for the State.

In recent years he has been a member of a team of scientists investigating the much publicised and now widely known problem of "Sheep infertility on clover pastures." Investigations have revealed the nature of the problem and have shown the presence in subterranean clover of an entirely new type of oestrogenic compound. They have made possible control in the field by suitable management practices.

He has also initiated a wide programme of research within the Institute of Agriculture, particularly in relation to pasture plant breeding and genetics, economic and farm manage-



ment surveys, factors influencing the nitrogen status of Western Australian wheat belt soils, the effects of rotation and cultural treatments on the "quality" of wheat, and the role of ruminal micro-organisms in sheep nutrition.

Professor Underwood is a foundation member of the Australian Institute of Agricultural Science and was one of its first fellows. In 1935, he was President of the Agricultural Scientists' Association of Western Australia, which body later became the Western Australian Branch of the Institute. He was Federal President of the Institute for 1952-53 and has the added distinction of being the recipient of the Australian Medal of Agricultural Science for 1952.

He was appointed Fellow of the Australian Academy of Science in 1954. His book "Trace Elements in Nutrition," published in 1956, is the first and only comprehensive text on trace elements.

In 1957 Professor Underwood was granted a Carnegie Travelling Fellowship to U.S.A., was Kearny Foundation Visiting Lecturer at the University of California, and was Schiff Foundation Lecturer at Cornell University.

8.—Concretionary Sandstones from the Learmonth Formation, Carnarvon Basin, Western Australia

By J. E. Glover*

Manuscript received—17th May, 1960

Bore cores of impure, fine- to very fine-grained quartz sandstones from the Jurassic Learmonth Formation contain small calcareous and sideritic concretions. Other important constituents of the rocks are widely disseminated siderite crystals, organic remains (shells, wood fragments, spores and probable algal fragments), pyrite and sparse haematite. Pyrite formed rapidly near the sediment-water interface, apparently from bacterial action in more or less enclosed micro-environments of putrefaction, such as wood cells and spores. Many minute spherical to subspherical pyrite grains, after solution in nitric acid, leave a cellular residue that closely resembles individual spores or spore fragments. The concretions formed shortly after the pyrite, before appreciable sedimentary compaction, and preserve delicate organic structures. A little haematite, probably formed elsewhere in oxygenated conditions, has survived. Deposition in a marine basin that may have been silled, and the presence of short-lived and varied micro-environments near the sediment-water interface, are suggested to explain the mineralogy and texture of the concretionary sandstones.

Introduction

The Learmonth Formation is a sequence of interbedded sandstone, conglomerate, siltstone and shale of Middle and Upper Jurassic age in the Carnarvon Basin, Western Australia. The formation is encountered between depths of 3,990 feet and 6,200 feet in West Australian Petroleum's Rough Range No. 1 bore, and is found in other nearby bores. It has been formally defined and briefly described by McWhae, Playford, Lindner, Glenister and Balme (1958). The Learmonth Formation is believed by those authors to be probably a condensed paralic facies equivalent of part of the Dingo Claystone, a sequence mainly of carbonaceous silty claystone and siltstone that was penetrated for 11,463 feet by Cape Range No. 2, without reaching the bottom.

Cores from the Learmonth Formation† in which concretions have been observed are as follows:

| Rough Range No. 1— | ft | ft |
|--------------------|-------|-------|
| core 18 | 4,441 | 4,444 |
| core 18 | 4,444 | 4,447 |
| core 18 | 4,447 | 4,452 |
| core 19 | 4,668 | 4,677 |

The top three specimens are impure, fine- to very fine-grained quartz sandstones containing calcite, shell and plant remains, siderite, pyrite, argillaceous material, black iron ores, haematite and muscovite. The bottom specimen is similar except that calcite and siderite com-

pose 50% of the rock. Siderite is present in most rocks of the Learmonth Formation in Rough Range No. 1. The proportion by weight of organic matter in the rocks has not been determined, but visual estimation suggests that the lowest specimen (from 4,668-4,677 feet) contains the most. Here, about 20% by volume of the concretion is made up of wood fragments, about 5% by shell fragments, and an indeterminate amount by other fine organic matter (probable algal remains, spores, etc.)

Petrography

As the concretionary rocks are similar, only one (core 18, 4,441-4,444 feet) will be described in detail.

Hand Specimen

The rock is dark grey and moderately well consolidated, and contains a light grey, irregularly shaped concretion about 4 cm long (Fig. 1). The most abundant mineral is very fine-grained angular quartz, and other recognizable material includes carbonaceous streaks, muscovite flakes and numerous shell fragments. The fine bedding around the concretion is highly distorted. The rock effervesces in patches with cold dilute HCl, but effervescence is more pronounced in the concretion.

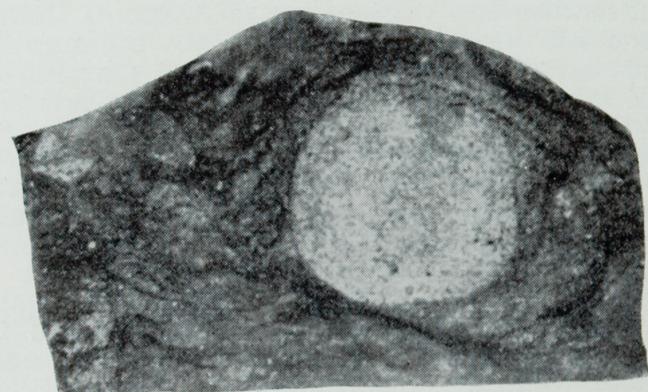


Fig. 1.—Calcareous concretion in very fine-grained, sideritic sandstone from 4441-4444 feet. Note the contorted bedding outside the concretion. Diameter of the concretion, which is about 4 cm long, is 2.5 cm.

Etched Surfaces

Inspection with a binocular microscope of a flat surface that has been etched in cold dilute HCl for several minutes shows that most of the cement in the concretion is calcareous, whereas it is not in surrounding areas. Where calcareous cement is dissolved away, numerous

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†Made available through the courtesy of West Australian Petroleum Pty. Ltd.

wood fragments with well preserved cell structures remain. Wood in the surrounding rock is almost all distorted and flattened.

Thin Section

Material outside the concretion.—Thin section studies with the petrologic microscope show that about 60% of the rock surrounding the concretion is made up of angular quartz grains, most with a diameter of the order of 0.08 mm. The matrix is made up partly of minute grains of yellow-brown siderite that commonly penetrate borders of adjacent quartz grains, giving them a ragged appearance. The siderite grains are generally rhombs about 0.01 mm in diameter, and their highest refractive index (ω) is close to 1.840. Apart from siderite, the matrix consists mainly of a brown to dark brown clay-sized paste that cannot be resolved under the microscope, although sericite shreds and finely divided organic material can be recognized in places.

Flakes of muscovite are fairly common, and are conspicuous because of their length (up to 1 mm) in the otherwise very fine-grained rock. Many flakes bifurcate and anastomose, being separated by aggregates of minute siderite euhedra (see Fig. 2). It is not clear whether the muscovite is authigenic, and has grown around the siderite, or whether siderite has grown along the (001) cleavage planes, forcing the flakes apart. Optical data for the muscovite are as follows: $\beta = 1.595 \pm .001$, $\gamma = 1.597 \pm .001$, $2V$ (measured on three flakes with the universal stage) = $39^\circ \pm 1^\circ$, $41^\circ \pm 1^\circ$, $44^\circ \pm 1^\circ$. These properties suggest a muscovite containing variable amounts of the picrophengite (Mg rich) molecule, but little of the ferrimuscovite (Fe rich) molecule (Winchell and Winchell 1956, p. 368).

Carbonaceous fragments and streaks are scattered throughout the rock (see Fig. 3), and are generally intimately associated with pyrite. The

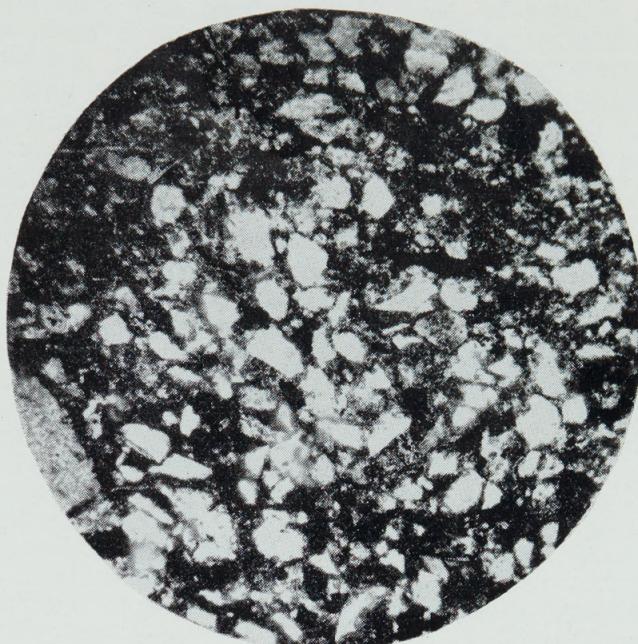


Fig. 3.—Thin section (transmitted light) showing texture outside the concretions in a core specimen from 4659-4668 feet. Note the ragged boundaries of many quartz grains. The grey matrix is mainly very finely divided siderite, and there are also black carbonaceous streaks and black opaque iron minerals. Diameter of field 1.7 mm.

nature of this association is best observed in reflected light, where it can be seen that pyrite grew in the wood cells, and has to some extent preserved the structure of the wood. Where the cells have not been occupied by pyrite however, the wood has been crushed and no trace of them remains. Pyrite is also found as minute spherical bodies (generally from 0.02 to 0.05 mm in diameter) and anhedral grains throughout the rest of the rock. Black opaque grains are ubiquitous, but angular, blood red haematite grains are far less common. A few black opaque grains are partly transformed to haematite, and very rarely, there are composite grains of haematite and pyrite. Other minerals noted include calcareous shell fragments and finely divided calcite, biotite, chlorite, feldspar and leucoxene.

The per cent composition of the rock outside the concretion is visually estimated to be:

| | | | |
|---|-------|-------|----|
| Quartz | ..... | ..... | 60 |
| Siderite | ..... | ..... | 12 |
| Calcite (including shell fragments) | ..... | ..... | 8 |
| Woody material | ..... | ..... | 5 |
| Heavy minerals (including pyrite) | ..... | ..... | 5 |
| Muscovite | ..... | ..... | 2 |
| Clay-sized cement, fine organic detritus and other minerals | ..... | ..... | 8 |

Concretion.—The concretion contains the same minerals as the surrounding rock, but calcite, both as shell fragments and as finely divided cement, is far more abundant. The structure of much of the organic material is far better preserved, however, and will be briefly described.

The structure of the wood has been well preserved (see Figs. 4, 5 and 6). Some of the cells are filled with pyrite, or partly filled by approximately spherical pyrite bodies, but the cell walls have not been replaced. Other cells contain



Fig. 2.—Thin section (transmitted light) of calcareous and sideritic concretion from 4444-4447 feet. Note plitting of the long mica flake in the centre of the field. Much of the mica outside the concretion has a similar appearance. Diameter of field 1.7 mm.

Heavy Minerals

Heavy minerals from the disaggregated rock were concentrated in bromoform. A black, opaque, slightly magnetic, generally angular mineral (apparently ilmenite) is abundant. The range in magnetic susceptibility of the grains suggests, however, that they are not pure ilmenite, but intimate mixtures in varying proportions, of ilmenite and magnetite. Strongly magnetic black opaque grains that include some perfect octahedra (magnetite), and red angular grains (haematite) are less common. Some grains are clearly composite, and are made up of haematite and black opaque mineral. There are also rare composite grains of haematite and pyrite. Zircon and brown tourmaline are fairly common as euhedral grains, but less common as rounded grains.

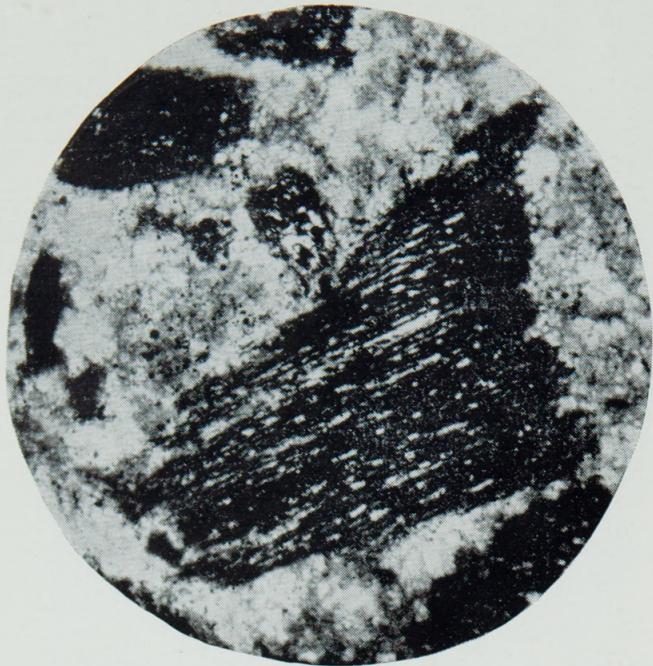


Fig. 4.—Thin section (transmitted light) of wood fragments in calcareous concretion from 4668-4677 feet. Diameter of field 1.9 mm.

minute pyrite crystals, apparently always octahedra, but their small size (usually less than 0.01 mm) precludes certain determination of the form of many of the crystals. Many wood cells contain no pyrite, and their preservation in the concretion contrasts with their destruction outside it.

A few pale brown, faintly anisotropic ovoid bodies with a length of up to 0.2 mm and a width of about 0.1 mm are present. Their origin is not known, for although they superficially resemble coprolitic pellets, almost all of them contain a core of black opaque mineral, or haematite or a composite grain of the two. In fact, it is notable that many of the haematite grains are so enclosed.

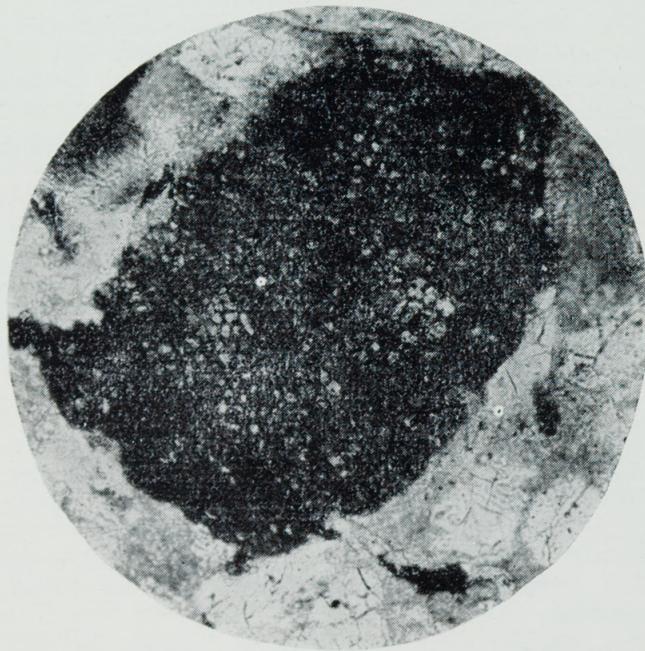


Fig. 5.—Thin section (transmitted light) showing wood fragment in calcareous concretion from 4441-4444 feet. Note preservation of cellular structure. Diameter of field 0.6 mm.

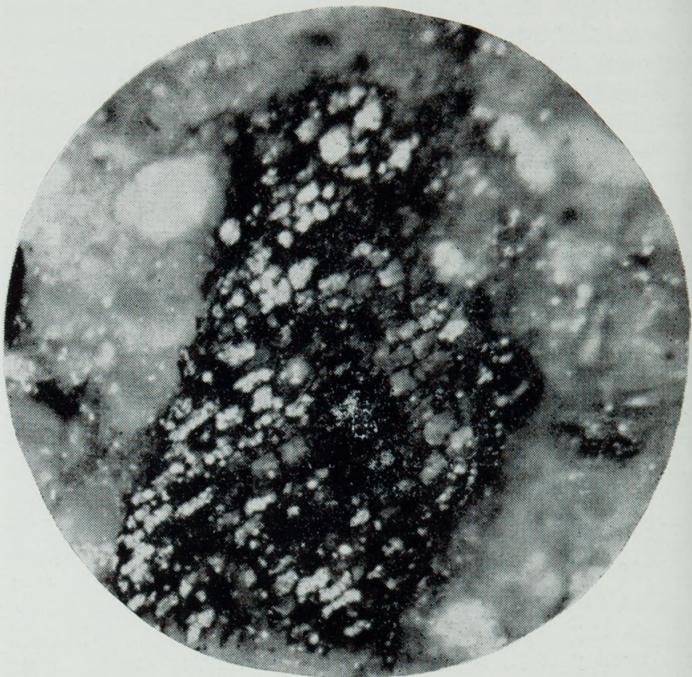


Fig. 6.—Thin section (reflected light) showing wood fragment in calcareous concretion from 4663-4677 feet. Note the preservation of wood structure and the pyrite (white) filling many of the wood cells. Diameter of field 0.7 mm.

Pyrite is almost as abundant as the black opaque grains, and it occurs in three forms, as small approximately spherical grains, as minute and rare octahedra, and as anhedral grains and aggregates. The spherical grains, which commonly range from 0.02 to 0.05 mm in diameter, although many are smaller, superficially resemble minute berries, and are like the frambooidal pyritic bodies described by Love (1958). The octahedra seem perfectly euhedral, but their small size (generally less than 0.01 mm) precludes precise observations. The anhedral pyrite attains lengths of up to 0.15 mm, and rarely far greater: some of the larger grains may be aggregates of the two other forms. Identification of the pyrite was confirmed by Mr. J. G. Kay, of the Department of Geology, University of Western Australia, from an X-ray powder diffraction pattern. It is free of marcasite.

When concentrated nitric acid is allowed to seep between a cover slip and a glass slide on which the spherical or subspherical pyrite grains

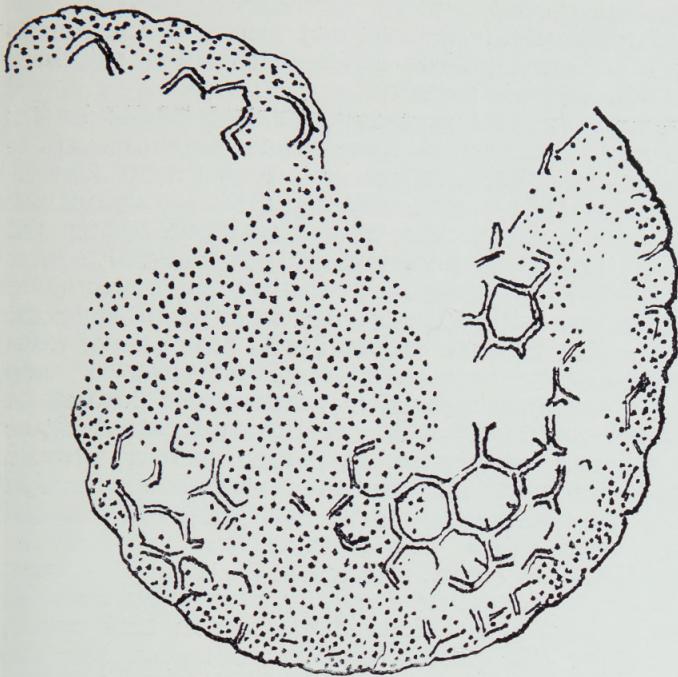


Fig. 7.—Sketch showing residue from a spherical pyrite grain after solution of the pyrite in concentrated nitric acid. The insoluble residual shell has been broken up by the effervescence, and much of it has floated away. Note the polygonal structure, and the grey cloudy material. The diameter of the unbroken shell is about 50μ .

have been placed, a reaction that commonly follows a characteristic sequence can be observed with the binocular and petrologic microscopes. As bubbles from the reaction gather in the liquid, a translucent to cloudy margin appears round the grains. When the margin has reached an eighth to one quarter of the diameter of the grain, it is generally split off by the force of the effervescence. Reaction with the core becomes stronger, and finally all pyrite disappears. Less generally, the hollow shell of translucent to cloudy material is not completely disrupted, and remains more or less intact after complete removal of the pyrite. It appears to be insoluble in the acid, where it has been observed to remain, apparently unaffected, for over one week.

Not all of the translucent material is identical in appearance. Nevertheless, although it is often broken up and obscured by cloudy matter, it can be shown in many grains to consist of a polygonal network. The most common of such networks are composed of six-sided polygons, each cell about 6μ in diameter. Five-sided polygons are also fairly common and four-sided cells have been observed. The cellular material thus appears to form an outer shell in the pyritic spheres, ranging mostly from 0.02 to 0.05 mm in diameter. The thickness of the shells is difficult to determine, and seems generally to be about 5μ . The thin cell walls consist of faintly anisotropic, colourless to pale brown material with a mean refractive index sensibly above that of the surrounding acid ($1.402 \pm .001$), and appear to be somewhat less than 1μ thick. In some grains, although a residue similar in optical properties remains after solution of the pyrite, no regular polygonal

structure can be detected. It is, of course, not unlikely that the structure, whatever its original nature, has been disrupted by the effervescence.

The residue left after solution of the anhedral grains consists of cloudy turbid material and fragments of the anisotropic, colourless to pale yellow material. Fragmentation has been too severe in all such grains treated, to establish the form of the insoluble material, as is possible with many of the spherical and subspherical grains.

Comparison of the insoluble shells remaining after acid treatment of the spherical and subspherical pyrite grains, with organic matter concentrated after treatment of the rock with hydrofluoric acid and centrifuging, reveals some notable similarities. Many of the spores in the organic residue show the same size range as the translucent acid resistant shells derived from the pyrite spheres, and unless flattened, have a similar shape. Moreover, the pattern on the surface of some of the spores can be matched with the polygonal structure of the translucent shells. The correspondence is strong enough to leave little doubt that spores and spore fragments have served as the site of deposition for many of the spherical and subspherical pyrite grains.

The general disruption of the translucent shells caused by effervescence during solution of the pyrite has prevented satisfactory photographs of them from being taken, and the appearance of a typical residue has been sketched (Fig. 7). Toward the end of the experimental work described above, Mr. B. E. Balme (Department of Geology, University of Western Australia) kindly drew the author's attention to a trilete spore in his collection from the Upper Devonian of Libya (Fig. 8). The spore is partly destroyed, and the pattern on the surface resembles that on much of the material extracted from the pyrite grains, and probably owes its origin to the same cause.

Discussion

Deposition of the Learmonth Formation was generally marine, and may have taken place in a silled basin, for the preservation of organic matter is characteristic of environments of restricted circulation. In this respect however,



Fig. 8.—Partly destroyed trilete spore from Upper Devonian of Libya. Note similarity of surface pattern to that shown in Fig. 7. Diameter of spore about 80μ .

it is worth noting the view of Krumbein and Garrels (1952, p. 23) that with sufficiently rapid sedimentation, organic matter may accumulate in an open sea neritic environment in mildly oxidizing waters. This is not incompatible with anaerobic or reducing conditions below the sediment-water interface. The Dingo Claystone, probably in part a deep water facies equivalent to the west, also contains fairly abundant, finely divided carbonaceous matter.

Broadly speaking, preservation of organic matter and formation of pyrite and siderite require anaerobic or reducing conditions. Haematite, on the other hand, forms in an oxidizing environment. There is also a sensitive pH control. Edwards and Baker (1951) show evidence for neutral to mildly alkaline conditions of formation for pyrite, and Krumbein and Garrels (1952, Fig. 8) suggest that pyrite and siderite generally form in alkaline conditions up to a pH of 7.8, whereas calcite normally requires slightly higher alkalinity (7.8+). The factors leading to formation and preservation of the above minerals in a marine environment are very likely, however, to be far more complex than those just indicated. Evidence from the Learmonth rocks suggests that short-lived and variable micro-environments played a large part in establishment of their ultimate mineralogy and texture. Some of these micro-environments will now be considered.

Pyrite

The intimate association of much of the pyrite with wood fragments has been noted. There is no evidence in these rocks that pyrite replaces wood, as it has been stated to do elsewhere by other authors. In the concretions, where the wood has not been squashed, pyrite completely fills some of the wood cells and in others forms minute spherical and subspherical grains, and even smaller crystals (apparently always octahedra). Outside the concretions, the cellular framework has disappeared from flattening, except where sufficient cells were filled with pyrite to preserve evidence of the original texture. Some such wood fragments seem in reflected light to have undergone very little compaction, for almost all the cells were so occupied, and preliminary examination might well give the incorrect impression that pyrite had replaced some of the wood. It is clear, however, that the pyrite formed before significant compaction of the wood, and other evidence given later accords with this view. Minute spherical and subspherical grains of pyrite are also scattered throughout the rock, outside the wood fragments.

The octahedron is the only crystalline form recognized here, and has been the dominant form in authigenic pyrite observed elsewhere by the author. It also figures prominently in descriptions of authigenic pyrite in the literature, although no special significance appears to have been attached to the fact. The findings of Kasizyn (1956) (as summarized in German by Mirtsching*) may, therefore, be of interest. Kasizyn noted that in pyrite from old metamorphic rocks examined by him, the forms de-

veloped include cubes, pentagonal dodecahedra and octahedra. Octahedral pyrite is anomalous and contains cobalt impurities which are held responsible for its habit.

The spherical and subspherical pyrite bodies in the Learmonth Formation resemble those noted in thin section by Brelié and Teichmüller (1953) and Balme (1956), and those separated from the Lower Carboniferous Oil Shale Group of Scotland by Love (1958). Love subjected his pyrite granules to nitric acid treatment with results very like those recorded here. He isolated microfossils from them, and named two new genera, *Pyritosphaera* and *Pyritella*, although their affinities could not be closely defined. He suggested that these organisms generated hydrogen sulphide as a by-product of the anaerobic decomposition of sulphur compounds, and that the gas reacted with iron from the surrounding medium, so precipitating iron sulphide on the organism. Although his genus *Pyritella* resembles some of the polygonal material described in this paper, a rather different origin is indicated for the latter. Organic matter that almost certainly included individual spores and spore fragments was the most likely nucleus for precipitation of many of the spherical pyritic grains of the Learmonth Formation. Precipitation took place before the spores were much compressed.

In summary then, the growth of pyrite occurred very early in the diagenetic history of the rock, probably on or just below the sediment-water interface. Its formation is best accounted for by the action of anaerobic bacteria in more or less enclosed spaces (spores and wood cells) where putrefaction was proceeding. The probable sequence of events has been set forth by Balme (1956). The bacteria reduce sulphate to sulphide at the expense of various organic compounds, and the hydrogen sulphide so formed reacts with ferrous hydroxide to give troilite (FeS). Subsequently, the troilite changes either to marcasite, in slightly acid conditions, or pyrite, in neutral to alkaline conditions.

Siderite and Calcite

Siderite is found almost throughout the Learmonth Formation in Rough Range No. 1, and its usual habit (minute euhedral crystals that penetrate adjacent quartz grains) indicates its authigenic origin. The siderite has changed from greyish to brownish in the laboratory, showing its susceptibility to oxidation, a property noted also by Pettijohn (1957, p. 145). Its formation in sediments, according to Krumbein and Garrels (1952, Fig. 8) is indicative of less strongly reducing conditions than those required for pyrite. In one concretion of which siderite forms most of the cement (from core 18, 4,444-4,447 feet) the wood fragments are perhaps not as well preserved from crushing as in the more calcitic concretions, but they are better preserved than in the surrounding rock.

It seems therefore that siderite and calcite (excluding calcite of shells) formed at about the same time. A sufficiently dense accumulation of either mineral resulted in a concretion: these concretions grew before appreciable compaction of the sediment, but after formation of the pyrite, which they enclose. The comparatively

*Mirtsching, A. (1959).—*Zbl. Miner.* 1957, (1): 109.

early growth of some types of concretion, which preserve contained organic matter from decomposition and crushing, has been known for some time, and there are interesting descriptions of the preservation of fishes (Weeks 1957) and plants (Brelie and Teichmüller 1953) by this means. The rather special conditions leading to formation of concretions are not, however, so easily explained. Weeks suggests that in some stagnant environments where the pH is normally too low for precipitation of calcium carbonate, alkalinity sufficient for deposition may be brought about locally by ammonia evolving rapidly from decomposition of proteinaceous (nitrogen bearing) organic matter. The abundance of shell fragments in the concretions of the Learmonth Formation may be significant but the processes leading mainly to precipitation of siderite instead of calcite in one concretion are not understood. Presumably they result from localized and critical combinations of Eh and pH.

Haematite

The presence of haematite, which is scattered sparsely through the concretions and surrounding rock as discrete grains, and combined with black iron ore, seems anomalous. Organic material, pyrite and siderite compose a mineral suite that accords with the interpretation of an anaerobic or reducing environment, whereas haematite is the product of a well aerated environment. It forms from iron silicates, magnetite, and probably from ilmenite as it develops rapidly in air at high temperatures from that mineral (Karkhanavala and Momin 1959). The presence of many grains of haematite and compound grains including haematite in ovoid pellets, perhaps of coprolitic origin, cannot be explained, but may be due to selection by some organism. A tentative explanation for the presence of haematite is that it formed earlier in a strongly oxidizing environment, perhaps for example, from jaspilites on the Precambrian Shield. It was swept into the basin of deposition with other clastics, and some of it survived the short-lived reducing environment to which it was then subjected.

Conclusions

Evidence from the composition and texture of the concretionary rocks from the Learmonth Formation in Rough Range No. 1 suggests de-

position in an oxygen deficient marine environment, near enough to the coast to receive a fair amount of plant material. The basin may have been silled during deposition of these rocks. Pyrite formed quickly close to the sediment-water interface, especially in micro-environments of putrefaction, such as cells of wood fragments and interiors of spores. Siderite then grew rapidly in an environment assumed to have been generally oxygen deficient and slightly alkaline. Slight variation from these general conditions resulted locally in precipitation of calcite. Concretions, either composed mainly of siderite or calcite, grew before appreciable compaction, preserving contained organic structures. Sedimentary material around the rigid concretions was compacted by superposed sedimentary beds which eventually attained a thickness of many thousands of feet.

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9.—The Fossil Mammalian Fauna of the *Burramys parvus* Breccia from the Wombeyan Caves, New South Wales

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A sample of Robert Broom's original material from the type locality and horizon of *Burramys parvus*, *Palaeopetaurus elegans*, *Pseudochirus antiquus*, *Macropus wombeyensis*, *Potorous tridactylus antiquus*, *Perameles wombeyensis*, and *Mastacomys wombeyensis* has been analysed. It is a very porous tufa crowded with bones, and with occasional fragments of coarsely crystalline calcite. Both are covered with a thin layer of fine dust and then with layers of cementing calcite. The deposit was probably accumulated by owls. The murids *Pseudomys oralis* and *Gyomys glaucus* and the phalangerid *Eudromicia lepida* are recorded from the Pleistocene for the first time. *Eudromicia lepida* is today confined to Tasmania. Those species in the fauna that are not extinct, occur today in eastern Australia. The climate of the district at the time of deposition was probably closer to that of modern Tasmania than to that of the locality today. The age of the deposit is probably Upper Pleistocene. More information about the ecology of modern species is needed and taxonomic revisions are required.

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Introduction

During the years at the end of the last century that the great palaeontologist and comparative anatomist, Robert Broom, worked in Australia, he described a fossil mammalian fauna which he collected from a depression on a hillside above the Wombeyan Caves, New South Wales (Broom 1896 *a*, *b*, *c*). The deposit is an exceedingly rich accumulation of small bones which are cemented in a limestone breccia. Among the animals which Broom described from this deposit is the problematical phalangerid *Burramys parvus* which is to date only known from this locality. Since its description, *Burramys* has played a considerable part in phylogenetic speculation on the origins of the Macropodidae, the family which includes the modern kangaroos and wallabies (see Ride 1956*a*). The fauna is also unique since it contains five other fossil marsupials and the

fossil murid *Mastacomys wombeyensis* (Ride 1956*b*) which are also to date unknown from other deposits.

The age of the fauna is at present unknown although both Broom and Ride consider it to be Pleistocene.

Cave breccias and the more obvious members of their faunas have long been well known from many parts of Australia and many of our known Pleistocene and sub-modern mammals have been described from them; but little is known of their absolute ages or even of their ages relative to each other. For certain localised areas at this time, C^{14} dates are becoming available and it is hoped that, in the near future, the absolute ages of at least the more modern of some of these faunas will become known. In the meantime, faunal comparisons still provide the most workable basis upon which to base relative ageing.

In this paper is given the result of an analysis of a sample of Broom's original material from his Wombeyan Caves deposit in terms of the specific identity and relative abundance of mammals which it contains. This provides a picture of the faunal composition of the type locality and horizon of *Perameles wombeyensis* Broom, *Palaeopetaurus elegans* Broom, *Burramys parvus* Broom, *Pseudochirus antiquus* Broom, *Macropus wombeyensis* Broom, *Potorous tridactylus antiquus* Broom, and *Mastacomys wombeyensis* Ride.

Method

In the Broom collection in the Anatomical Museum at Edinburgh there are a number of large pieces of breccia which contain the remains of many individual mammals. Nine of these pieces have been broken down by the acid-technique (see Ride 1956*a*) so that all the contained bones have been freed; the separate bones have then been identified so that some quantitative estimate of abundance can be made. Owing to the fact that no associated remains (i.e. associated as in life) have been found, it has not been possible to identify postcranial fragments with any certainty, so that this analysis is entirely based upon those fragments which are tooth-bearing.

Samples containing the remains of a large number of individuals which have disintegrated before being preserved present a problem in that there are different methods which might be used in the estimation of the total number of individuals present. Here no hard and fast rule has been adhered to such as that of only

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recording right mandibles, but, if in one species there are found to be four right fourth lower premolars then it is recognized that there must be at least four individuals present in the sample. Another species might have the number of individuals estimated by another feature.

It will be seen that some of the species described by Broom are not included in the table of relative abundance (Table I). These missing species happened not to be represented in the sample of nine pieces of breccia. A list of the total known fauna of the breccia is given in addition to the table of relative abundance.

The identification of new specimens of marsupials of Broom's fossil species was made by comparing all specimens with specimens identified by him and included in his Edinburgh Collection. No revision of the status of these species has been made. *Eudromicia lepida* was not previously obtained by him and, in this case, the five specimens (mandibles and maxillae) were compared with the excellent series in the British Museum (Nat. Hist.).

The Muridae present a greater problem in identification since there is a superabundance of named forms, particularly in the *Pseudomys* group of genera, some of which are certainly synonyms. Since most of the marsupial genera represented in the breccia are also included among the Recent fauna of Australia, I have assumed that most or all of the murines would also prove to belong to Recent Australian murine genera. Direct comparison with specimens in the British Museum was made with all of these.

Australian Murinae may be divided into three groups (see Tate 1951) which are: Group 1. "modern introductions". e.g. *Rattus rattus*, *R. norvegicus*, *Mus musculus*; Group 2. "young endemics", e.g. species of *Rattus* which have probably evolved in Australia, including the *R. assimilis* and *R. lutreolus* species groups; Group 3. "old endemics", i.e. Murinae of genera peculiar to Australia and the adjacent islands.

Results

Fauna

Murinae: Groups 1 and 2.—In the identification of fossil murines, specimens of *Rattus* are most easily separated from the rest by means of the characteristic root pattern of the first molar (see Jones 1922) as shown in Fig. 1. No species of *Rattus* were encountered in this deposit, nor was *Mus* (sens. strict.).

Murinae: Group 3.—Of the old endemics, the following genera at present occur in continental Australia and any might have been expected to occur in the sample: *Pseudomys*, *Gyomys*, *Thetomys*, *Leggadina*, *Notomys*, *Mastacomys*, *Leporillus*, *Zyzomys*, *Mesembriomys*, *Conilurus*, *Laomys*, *Uromys*, and *Melomys*. Of these genera the last two comprise the Australian mainland representatives of the *Uromys* genus-group which is probably papuan in origin. Tate (1951, p. 283) believes that this group was derived independently from a *Rattus*-like ancestor. The Australian species of the *Uromys* group are mostly tropical forms and are probably fairly recent arrivals in continental Australia.

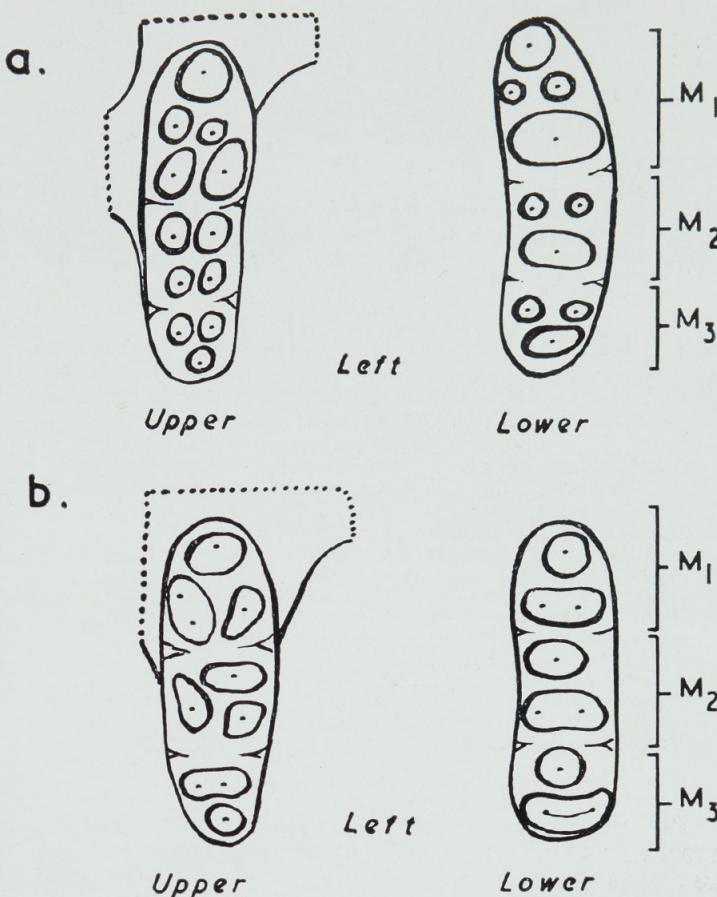


Fig. 1.—The alveolar cavities of Australian murines after Wood Jones (1922). (a) *Rattus greyi* (b) *Leporillus jonesi*.

One would not expect to find them in a southern (New South Wales) Pleistocene fauna and none were obtained.

The remaining old endemic genera constitute the *Pseudomys* genus group. Only three species of this group were obtained and they were found to belong to *Mastacomys*, *Pseudomys*, and *Gyomys*. A large series of type specimens of these genera is available in the British Museum (Nat. Hist.) and upon comparison with these, the specimens in the deposit were found to agree most closely with the types of *Pseudomys oralis* Thos. and *Gyomys glaucus* Thos. The *Mastacomys* was new and has received the name *Mastacomys wombeyensis* Ride (1956b).

Marsupialia.—In addition to the species already described by Broom, specimens of *Eudromicia lepida* were obtained.

The results of the faunal analysis are summarized in the following list and in Table I.

The following species of Mammalia occur in the deposit:

MONOTREMATA

1. *Tachyglossus* sp. Remains are too fragmentary to allow of specific identification.

MARSUPIALIA

2. *Antechinus flavipes* (Waterhouse.)
3. *Phascogale tapoatafa* (Meyer.)
4. *Thylacinus cynocephalus* (Harris.)
5. *Perameles wombeyensis* Broom.
6. *Phalangeroides*
7. *Cercartetus nanus* (Desmarest.)

7. *Eudromicia lepida* (Thomas.) New record.
8. *Petaurus breviceps* Waterhouse.
9. *Palaeopetaurus elegans* Broom.
10. *Burramys parvus* Broom.
11. *Pseudochirus antiquus* Broom.
12. *Potorous tridactylus* (Kerr.)
13. *Macropus wombeyensis* Broom.

RODENTIA

Muridae

14. *Pseudomys oralis* Thomas. New record.
15. *Gyomys glaucus* Thomas. New record.
16. *Mastacomys wombeyensis* Ride (Ride 1956b as new species.)

TABLE I

Relative abundance of individuals in the fauna of the *Burramys parvus* breccia of the Wombeyan Caves, N.S.W. Only those species which were found in the test sample mentioned above are included.

| Species | Number of Specimens | Minimum number of individuals |
|-------------------------------|---------------------|-------------------------------|
| <i>Antechinus flavipes</i> | 14 | 4 |
| <i>Phascogale tapoatafa</i> | 2 | 1 |
| <i>Perameles wombeyensis</i> | 17 | 3 |
| <i>Cercartetus nanus</i> | 26 | 6 |
| <i>Eudromicia lepida</i> | 5 | 2 |
| <i>Palaeopetaurus elegans</i> | 7 | 2 |
| <i>Pseudochirus antiquus</i> | 11 | 3 |
| <i>Potorous tridactylus</i> | 4 | 1 |
| <i>Pseudomys oralis</i> | 10 | 3 |
| <i>Gyomys glaucus</i> | 87 | 17 |
| <i>Mastacomys wombeyensis</i> | 1 | 1 |
| (<i>Burramys parvus</i>)* | (9) | (3) |

Petrography of the Deposit

The petrography of the *Burramys parvus* breccia has not previously been investigated and Dr. Pamela Lamplugh Robinson of the Department of Zoology, University College, London kindly did this for me. The following is an extract from her report on the material (personal communication):

Hand specimen.—A very porous tufa crowded with bones, and with occasional fragments of coarsely crystalline calcite. No layering is apparent, and there is no directional orientation of the bones. The bones do not appear to be abraded by an agent of transport such as water or wind.

Thin section.—The fragments of crystalline calcite, and the majority of the outer surfaces of the bones are covered with a thin layer of extremely fine brownish dust. Then follows a layer or layers of calcite containing a fine dispersion of dust. The remaining interstices between calcite fragments and bones may either be unfilled with cementing calcite (in which case the cavity commonly has a lining of a thin layer of clear calcite) or be filled with clear cementing calcite. The interior of the bones may be hollow, or lined with a thin layer of calcite, or completely filled in with calcite.

Discussion

Several aspects of this breccia and fossil fauna require discussion. First, there is the provenance of the bones and the mode of deposition of the deposit; second, there are zoogeographic and palaeoclimatic implications; and third, there is the age of the fauna. Finally, certain general principles emerge.

*Three of the pieces of breccia were chosen for treatment because a mandible of *B. parvus* was present on the surface so that the results for this species are not strictly comparable. If these three specimens are ignored, the results for *Burramys* are six specimens comprising at least one individual.

Provenance of the Bones and Mode of Deposition

Great concentrations of small bones such as occur in the *Burramys* breccia are a familiar feature of many Australian cave deposits. For example, the cave earth of Hastings Cave, Jurien Bay, Western Australia, which is comparably rich in bone to the *Burramys* breccia, is in places 11 ft thick. Most of the remains of the many hundreds of thousands of individuals which go to make up the bulk of these deposits appear to have been transported into the caves from outside. Further, the bones seem always to have been moved after the bodies have decomposed, since it is only seldom that bones associated in life remain so in the deposit. In Hastings Cave it appears that some of the material is washed down into the entrance. The entrance is a sink hole into which a collapse has left an inclined ramp which leads from the present day surface of the ground through the arched entrance of the main cavern. Bones deposited in the sloping entrance ramp or within the arch itself are thus washed further back into the cave. Some layering is apparent.

In the *Burramys* breccia however, no stream bedding or layering of any kind, or sorting of the bones could be detected by Dr. Robinson, and further, the deposit is extraordinarily free from clay, silt and sand. These facts would appear to discount any suggestion that the bones were transported into the cave by water as some have been at Hastings cave.

Dr. Robinson does not consider that the deposit is wind-accumulated because there are no sand grains or signs of vegetable debris which might be expected if the remains had blown into the cave from outside. She suggests that animal transport is the most likely means by which the bones accumulated and points out that the broken state of these small bones would appear to indicate accumulation by some predator.

The character of the matrix gives further indication of the conditions under which the deposit accumulated. It consists first of fine dust which probably penetrated from outside the cave or which may even have been derived from the ceiling of the cavern itself by decomposition of the limestone and the freeing of contained impurities. This coating of fine dust possibly marks arid periods during the accumulation of the bulk material of the deposit which comprises the bones and the fragments of coarsely crystalline calcite. The bulk of the matrix is a finely crystalline calcite cement which was probably laid down by percolating water. Dr. Robinson considers that deposition was probably slow and the calcite may have been laid down intermittently. This slow rate of deposition was suggested to her by the great concentration of bones in the relatively scanty matrix and by the covering of fine dust which must have taken some time to settle.

An additional point of importance in the understanding of this deposit is the fact that the majority of the remains appear to be those of members of species of small body-size, or of immature individuals of larger species. For example, the larger forms represented in the

breccia are *Pseudochirus antiquus*, *Potorous tridactylus*, *Perameles wombeyensis*, *Thylacinus cynocephalus*, and *Macropus wombeyensis*. By the examination of dental wear of isolated teeth, and the stage of tooth eruption reached in mandibles and maxillae, it is possible to obtain a rough estimate of the age of individuals at the time of death; and examination of the material I have prepared shows that, with the exception of a single specimen of *Perameles wombeyensis*, all specimens of the first three species for which age can be estimated are juveniles. This great accumulation of the remains of animals of small size would appear to have been assembled by some definite form of selection. In the case of *T. cynocephalus* and *M. wombeyensis* even the juveniles are large animals as compared with the other mammals of the fauna and these two species appear to be atypical of the deposit in this respect. Remains of these are rare in the breccia and it is possible that they represent fortuitous inclusions. In recent years, I have frequently found the mummified remains of larger mammals among the bones of smaller ones on the surfaces of cave floors. These caves are at present accumulating the dead remains of predominantly small-mammal faunas in Western Australia and the larger bodies which occur in them appear to be the corpses of individuals who either seek refuge in caves in times of distress, e.g. *Macropus ocydromus*, *Protomodon irma* and *Vulpes vulpes*, or to be those of individuals which habitually frequent caves and thus stand a reasonable chance of dying in them, e.g. *Macropus robustus* and *Tachyglossus aculeata*.

Broom (1896c) did not recognize that the sample was biased and assumed that the assemblage gave a picture of the whole fauna of the district at that time. He noticed that most of the forms might be classed as "feeble and defenceless" and he concluded from this that they probably flourished "owing to the absence or scarcity of natural enemies" instead of realising that in all probability they died and were included in the deposit because they were feeble and defenceless.

The identification of the predator presents a tantalizing problem. The presence of the remains of *Thylacinus* in the deposit would suggest that it and *Sarcophilus* might have been responsible since they are both frequently found together in mainland cave fillings of the late Pleistocene. However, large carnivorous mammals frequently leave some associated bones of their prey such as bones of the feet and these are not to be found in the deposit. The cave-dwelling carnivorous bat *Macroderma gigas* presents a further possibility. Mr. A. M. Douglas and I have examined the accumulated debris of living colonies of these bats in parts of the Pilbara district of Western Australia in recent years. These deposits are characteristic in that they frequently contain the remains of *Macroderma* itself and moreover contain a large proportion of avian remains but neither of these characters is possessed by the *Burramys* breccia. Finally, owls make use of caves as roosting places and owl pellets of *Tyto alba* and *Ninox connivens* which I have examined lead me to

believe that these birds of prey are mainly responsible for the accumulation of the bones in the *Burramys* breccia. Main (1959) has come to a similar conclusion with respect to the extensive deposits of small mammal bones in the caves of the Western Australian aeolianite, and Dr. J. T. Robinson of the Transvaal Museum has told me that almost identical deposits are at present being formed by owls in the caves of the Transvaal.

Zoogeography and Palaeoclimate.

The fauna of the *Burramys* breccia can be divided into three groups:

- (1) Those which are extinct today e.g. *Burramys parvus*, *Palaeopetaurus elegans*, *Mastacomys wombeyensis*, *Perameles wombeyensis*, *Pseudochirus antiquus*, and *Macropus wombeyensis*.
- (2) Those which certainly occurred in the area in historic times e.g. *Tachyglossus*, *Antechinus flavipes*, *Phascogale tapoatafa*, *Cercaertus nanus*, *Petaurus breviceps*, *Potorous tridactylus*, *Pseudomys oralis*. Possibly *Perameles wombeyensis*, *Pseudochirus antiquus* and *Macropus wombeyensis* may prove to be chrono-subspecies of Recent species like *Potorous tridactylus antiquus* and as such could be listed here. *Gyomys glaucus* should also probably be included in this group although its present distribution is Southern Queensland (Tate 1951).
- (3) Those which have only existed in historic times in Tasmania, e.g. *Thylacinus cynocephalus* and *Eudromicia lepida*.

The conclusions which can be derived from the evidence of these groups are as follows:

- (1) Some of the extinct forms have not as yet been found in any other known deposit of Quaternary or Tertiary age and nothing is known of their distribution. Nothing can be derived from the presence of these.
- (2) Of those species which certainly occurred in the area in historic times, *Tachyglossus* and *Phascogale tapoatafa* are widespread in Australia and although local forms of them probably have specific requirements in relation to climate it has not been possible to relate the morphology of the fossils to that of present geographical races and climatic information has not resulted. *Petaurus breviceps* is similarly distributed through both summer and winter rainfall areas in Australia, but here there is some evidence that it is confined to areas of reasonably high rainfall, e.g. south-eastern and eastern Australia, Cape York, the Northern Territory, the Kimberley District, and New Guinea. *Cercaertus nanus*, *Potorous tridactylus*, *Antechinus flavipes*, *Pseudomys oralis* and *Gyomys glaucus* are as far as I can determine confined to areas of abundant rainfall or at least reliable winter rainfall (see

Keast 1959, Fig. 4). This would seem to indicate that the climate of the area at the time of deposition was not much more arid than it is at present.

(3) Two of the mammals of the fauna (*Thylacinus cynocephalus* and *Eudromicia lepida*) are today only found in Tasmania. A case may be made that the mainland extinction of the Thylacine followed the introduction of the Dingo into continental Australia in the sub-modern period, but it is possible that here we do not have cause and effect. Climatic change may be involved. In addition, although we possess scant ecological knowledge, it seems unlikely that the mainland population of *Eudromicia lepida* has become extinct through competition. Its closest relative, and apparent competitor in the mainland Pleistocene, is *Cercaertus nanus* which survives it on the mainland at present but both species still co-exist in modern Tasmania. The extinction of *E. lepida* and *Thylacinus* on the mainland may well be the result of a general environmental change which has resulted from slowly increasing aridity. There is evidence that this has gone on since the last pluvial period and that the present day climate in parts of Australia is as arid, or even more arid, than any period in the Pleistocene (Tindale 1955).

The occurrence of these two Tasmanian forms in the fauna increases the probability that the climate was somewhat wetter and colder at the time of deposition than it is at present.

The occurrence in this area of a Pleistocene fauna which required a colder and moister environment than the area possesses today is not surprising. Only a hundred miles or so to the south, the Kosciusko region was glaciated three times during the Pleistocene and glaciers extended down to 4,800 feet. They covered some 150 square miles (David 1950). At approximately 2,000 feet, and only 150 miles from the centre of the glaciations, the Wombeyan Caves must on several occasions have had a periglacial climate which would have been colder and wetter than at present.

The Age of the Fauna

The advances of geophysics have been such that modern palaeontologists can, in many cases, know the absolute ages of their materials. In the case of the *Burramys* breccia this has not yet been possible. Insufficient bone, and no plant remains, are available for C^{14} dating. However, the palaeoclimatic evidence, which indicates a slightly colder and wetter climate than the area enjoys today, suggests, when taken in conjunction with the nature of the fauna, an age somewhat later than the last pluvial period of the Pleistocene.

Dr. K. P. Oakley of the British Museum (Nat. Hist.) has tried to obtain data by physical methods through which an age relative to other known Australian cave deposits might be achieved, but no significant information resulted. This was largely because sufficient reliable material upon which comparison might be based was not available.

If an attempt is made to correlate faunas of known cave deposits little success is achieved, simply because relevant data are not available. The reasons for this are twofold. First, most authors working in these deposits, with the exception of a few like Finlayson (1933), have not recorded on a total faunal basis, merely confining themselves to descriptions of some of the specimens. Secondly, most of the Pleistocene fossils which have been described are of relatively large animals which are not comparable with these of the Wombeyan Caves. For example, the most obvious recorded faunal assemblage with which to compare the *Burramys* fauna is that of the Wellington Caves, but the recorded fauna from them is one of large mammals. However, the remains of small mammals do occur in this Pleistocene fauna but they are difficult to prepare by manual methods, and when prepared in this way are often even more difficult to identify. Lydekker (1885, p. 227) catalogued specimens of *Mastacomys fuscus*, *Conilurus albipes*, and *Pseudomys lineolatus* from the Wellington Caves, in the British Museum Collection; these identifications have been confirmed by me and I have obtained further specimens of *P. lineolatus* and *M. fuscus* from a piece of breccia from these caves which was collected by D. M. S. Watson and is now in his collection.

In the geographically close Wellington and Wombeyan Caves it may be chronologically significant that both *Pseudomys* and *Mastacomys* are represented by different species, but, in the case of *Pseudomys*, since both species (see Tate 1951) are extant today it may merely reflect a slight ecological difference between the two areas. Another alternative is that the two species are biologically one since my specific identifications merely record that each specimen is morphologically closer to the type specimen of its assigned name than to any other.

The differences between the species of *Mastacomys* can be similarly dismissed. At first sight the fact that *M. wombeyensis* of the Wombeyan Caves' fauna is extinct and not otherwise known, could possibly imply an even greater age for the fauna than is indicated by the general faunal picture and the evidence of climate. *Mastacomys fuscus* and its subspecies are widely distributed in Pleistocene and Recent south-eastern Australia, and it even extends into cave deposits as far north-west as the Flinders Range of South Australia where it is associated with such typical giant Pleistocene forms as *Thylacoleo* (see Ride 1956b). In the Wellington Caves it appears to be associated with *Diprotodon*, *Nototherium*, *Thylacoleo*, *Sthenurus* and *Procoptodon* etc., but there is insufficient stratigraphic evidence to be certain. The *Burramys* fauna could thus be older than these faunas. Unfortunately the validity of the species *Mastacomys wombeyensis* still re-

quires confirmation. It is still only known from a single specimen in this fauna which contains no *M. fuscus*. It differs from *M. fuscus* in two characters, one of which (the great width of the cheek plate in almost unworn teeth) is so distinctly different from that of all other specimens of *M. fuscus* (including *M. f. mordicus*) known to me, that I consider it unlikely that it is not a separate species. The other character, an extra cusp on the third molar, is possibly less reliable. Extra cusps on the molars of the murids of the *Pseudomys* group are not uncommon, for example, the presence of a subsidiary cusp on the inner front edge of M^1 is one of the distinguishing characters of the genus *Thetomys*, but 30% of all specimens of *Pseudomys* and *Notomys* in the collections of the British Museum (Nat. Hist.) also have this as an "abnormality". However, that a character is unreliable in one genus need not necessarily render it so in another. The presence of two apparently unrelated abnormal conditions in a unique specimen is unlikely, but more material is needed to establish the validity of the species.

Even if we accept the validity of *M. wombeyensis*, it is in no way morphologically ancestral to *M. fuscus* (see Ride 1956b, pp. 436, 7) and there are no phylogenetic reasons as to why it should occur earlier in time. There can be no reason why the occurrence of two species of *Mastacomys* in eastern New South Wales during the Pleistocene should not be synchronous.

There can be little doubt that the great abundance of murine fossils in the cave breccias will be of great help in future faunal comparisons. Before they can be used, however, we must have a realistic taxonomy of them. Keys to their identification which depend on characters other than numbers of mammae etc., and which provide for the statistical appreciation of individual variation, must also be made before the working palaeontologist can use these species because working collections which are comprehensive enough are not generally available for comparison.

A further distinction between the faunas of the Wombeyan and Wellington caves is one pointed out by Broom (1896c). *Trichosurus vulpecula* is absent from the *Burramys* breccia while it is present in the Wellington Caves fauna (Brit. Mus. (N.H.) No. M10789). The absence of *T. vulpecula* from the *Burramys* breccia led Broom to suggest that the deposit accumulated before the species came into the district. Absence from the palaeontological record is always an unsound basis for argument and in this case it is particularly so because the fauna represented is clearly only a selected part of the whole. Even if *Trichosurus* were resident in the area at the time of deposition, adult specimens of it would fall well outside the size range of the included species and it would at most only be represented by occasional juvenile individuals. *Trichosurus* is widespread throughout the greater part of Recent Australia. It is one of the most successful and adaptable phalangerids. If Broom is right in his contention, then the Wombeyan Caves' fauna is an earlier one than that of the characteristic "giant"

fauna of the Wellington Caves. A similar fauna of giant marsupials including *Nototherium* and *Sthenurus* (Mammoth Cave) in Western Australia has recently been dated as $>37,000$ years (E. Lundelius, personal communication C^{14} date).

In conclusion then, we may say that comparison of the Wombeyan Caves fauna with Recent faunas, together with palaeoclimatic considerations suggests that the fauna is Upper Pleistocene and probably dates from the period since the last pluvial. More slender arguments can be brought forward that the fauna is older than that of the Wellington Caves.

General Considerations.

During the preceding paragraphs one fact has clearly emerged and that is that we do not yet know enough about our faunas to provide a basis for any real comparative discussion. The work which will form the necessary preliminary to the quantitative comparison of faunal assemblages, and their palaeoecological interpretation, is yet to be done. We do not even know much of the ecological interrelationships within modern Australian mammalian communities, and this knowledge must necessarily form one of the premisses of any logical argument in the interpretation of the environmental conditions under which fossil faunas have lived.

In our present state of knowledge, not even fully valid qualitative comparisons can be made because of the uncertain value of many of our species. A number of the species of our fossil and modern mammals are suspect because authors have not made adequate comparisons with other known, and obviously similar, forms. Further, although type specimens are the basis of zoological names, zoological species comprise populations with ranges of variation which, if unknown, can still be more or less predicted statistically in so far as measurable characters are concerned. It is against these ranges of individual variation that specimens which are suspected of belonging to new species must be compared and not merely with the types. The types may actually represent peripheral examples in the range of the species. New names made without biologically intelligent comparison do not advance our knowledge. They merely contribute to the existing confusion.

Acknowledgments

I wish to acknowledge with gratitude the help given me by Drs. K. P. Oakley and P. Lamplugh Robinson. Mr. A. M. Douglas examined deposits left by colonies of *Macroderma* with me, and Mr. B. E. Balme and Dr. J. Glover ascertained the thickness of the Hastings' Cave deposits for me. Drs. A. J. Cain and A. T. Hopwood have spent much time with me in most useful discussion. I am also grateful to Dr. E. Lundelius for allowing me to quote his unpublished C^{14} date for the Mammoth Cave fauna. Finally, the work would not have been possible except for the way in which the Professor of Anatomy, the University of Edinburgh; Professor D. M. S. Watson, F. R. S.; and the British Museum (Natural History); made their

specimens available to me for study. Much of the work was done while I held a Christopher Welch Research Scholarship in the University of Oxford. My colleagues Drs. G. F. Mees and A. R. Main read and criticised the manuscript.

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Addendum

(15 August 1960)

In July 1960 I was enabled, unexpectedly, to visit Broom's locality at the Wombeyan Caves. The caves are in a U-shaped ridge of hill which lies as a barrier across the path of a small stream which flows between the arms of the U. The stream disappears into a cave which carries it through the ridge and out of the other side. The ridge contains a labyrinth of caves, the Wombeyan Caves, which open to the exterior as sinkholes.

The Broom locality is well-known to the Caretaker of the Wombeyan Caves Reserve and is a small pocket of breccia in what was probably a solution pipe at one side of a depression on the top of the ridge. This depression is an old cave floor and is littered with typical cave debris. The solution pipe containing the breccia is within ten yards of a sink-hole. This hole is one of the Wombeyan Caves and is called the Guineacor Cave. The old cave floor and the *Burramys breccia* appear to be much older than the modern Guineacor Cave and I propose for them the names Broom Cave and Broom faunal assemblage. To call them by the name of the Guineacor Cave would be misleading.

Since Robert Broom collected at this locality, specimens have been collected by at least Professor R. A. Stirton, Mr. H. O. Fletcher, Mr. J. Mahoney, and myself. There appears to be little of the breccia left today and what remains is rigidly protected by the New South Wales Tourist Bureau and the Caretaker, Mr. Clyde Stiff, to whom I am most grateful for his assistance.

10.—Accessions of Sulphur in the Rainwater at Perth and Nedlands, Western Australia

By D. P. Drover*

Manuscript received—16th February, 1960

Analyses of rainwater for Perth and Nedlands in Western Australia were made from 1957 to 1959. Both stations are coastal and the sulphur accessions ranged between 1.2 and 6.0 lb/acre/year; these were not related to the amount of rainfall.

These amounts of sulphur are lower than those previously reported from Western Australia and from European and North American workers. The amounts of sulphur are regarded as insignificant for crop growth.

Introduction

Attention has been drawn to the low sulphur content of certain Australian soils. The relevant literature has been reviewed by Stephens and Donald (1958) who also discuss the limited amount of published work on the sulphur content of Australian rain. With such scant information it is impossible to ascertain the exact significance of rainfall in affecting the sulphur status of Australian soils.

Sulphur has been reported to be present in overseas rainfall in amounts which can favourably affect the sulphur content of the soil (Eriksson 1952).

Hutton and Leslie (1958) have shown for two Victorian coastal centres, that up to 7 lb sulphur/acre/year are received at Cape Bridgewater and 3 lb acre/year at Warrnambool. The amount of sulphur in the rain decreased to less than 2 lb acre/year at localities situated further inland. Hingston (1958), also at Perth, with a similar annual rainfall to the Victorian centres found that the amount of sulphur is between 8 and 10 lb acre/year. He concluded, as did the Victorian authors, that the sulphur content of rain was very low by European and North American standards. This paper is intended to augment the information on the sulphur content of Australian rain.

Material and Methods

Localities

Rainwater samples were collected, during 1957 and 1959 at the Institute of Agriculture, Nedlands, four miles west of Perth and at the Perth Observatory. Both localities are fairly removed from industrial contamination and are about four miles from the coast.

Collection Methods

Rainwater was collected in gallon polythene bottles fitted with a polythene funnel. The bottle and funnel were housed in a wooden box which had a series of wire spokes fitted to its

outside edge at the top to prevent birds from alighting and contaminating the sample. The height of the collection unit from the ground to the top of the box was 4 ft 6 ins.

Samples of water were taken after periods of rain, filtered through a washed filter paper and stored in polythene bottles. A few drops of chloroform were added to prevent algal and other biological growth.

Analytical Methods

Sulphate-sulphur was estimated in the samples by the micro-method of Johnson and Nishita (1952). In this method sulphates were reduced to hydrogen sulphide by a mixture of hydroiodic acid, formic acid and red phosphorus. The resulting hydrogen sulphide was estimated as methylene blue in an E.E.L. Absorptiometer using a red (608) filter and a 1 cm cuvette. 25 or 50 ml of rainwater were evaporated to dryness in the boiling flask of the special digestion distillation apparatus.

The 1959 samples were analysed by the barium chloride (ethylene-diamine-tetra-acetic acid) (E.D.T.A.) back titration method of Bond (1955). This procedure was adopted when reproducibility of the sulphur values could not be obtained owing to impurities in a batch of reagents. In the E.D.T.A. method, 200 ml of rainwater were analysed and the endpoint of the Eriochrome Black indicator was determined optically by means of an E.E.L. Titrator.

Results and Discussion

The sulphur data for 1957-1959 are given in Table 1. Considerable differences occur in the amounts of sulphur between the three years and these are not related to the amount of rain. The sulphur content of the rain is low.

TABLE I
Quantity of Sulphur in Rainwater 1957-1959

| Locality | Rainfall Analysed (Inches) | Total Rainfall (Inches) | Sulphur (lb/acre) |
|------------------|----------------------------|-------------------------|-------------------|
| <i>Nedlands—</i> | | | |
| 1957 | ... | 29.50 | 3.26 |
| 1958 | ... | 30.51 | 1.21 |
| 1959 | ... | 24.02 | 4.78 |
| <i>Perth—</i> | | | |
| 1957 | ... | 32.11 | 3.81 |
| 1958 | ... | 31.23 | 1.21 |
| 1959 | ... | 24.23 | 5.97 |

*Institute of Agriculture, University of Western Australia, Nedlands, Western Australia.

Perth and Nedlands may be considered as coastal as they are both about four miles from the ocean. The sulphur values are lower than the 8-10 lb/acre/year previously reported by Hingston (1958) and are more comparable to the values of Hutton and Leslie (1958) in Victoria.

At both localities in 1959 the sulphur values are considerably higher than those of the two previous years, despite a much lower rainfall. No explanation can be given, and the fact that the analytical method used was different is not considered to be a contributing factor. It has been mentioned above that the titration method was adopted in 1959 because of the difficulty of obtaining a satisfactory colorimetric determination due to impurities in a batch of reagents. When this factor was rectified a trial was done to estimate the errors involved. The standard error between the titration and colorimetric method was 0.084 p.p.m. sulphur. The local data of Hingston covered two year's observations and there was a difference of 2 lb/acre/year. The data of Hutton and Leslie apparently are only for a single year. A greater amount of atmospheric dust in the dry year of 1959 may account for the higher sulphur figures.

Eriksson (1958) quotes a figure of 10 Kg/hectare (approx. 9 lb/acre) as being the characteristic sulphur value for unpolluted air. The results given here do not support this contention in contrast to the previous findings of Hingston in Western Australia. The data are more comparable to those of Hutton and Leslie for two Victorian coastal stations.

Acknowledgments

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11.—Stratigraphy of the Boogardie Group

By D. J. Forman*

Manuscript received—22nd September, 1959

The Boogardie Group at Mount Magnet, Western Australia forms part of a succession of Archean rocks known as the "Older Greenstones." The group overlies the Lennonville Beds and other older rocks and is overlain by an unknown thickness of sedimentary and igneous rock. It has developed minerals typical of the greenschist facies of metamorphism.

Nine formations make up the group. These are in ascending order: Poverty Flat Formation, Jupiter Jaspilite, Mount Magnet Greenstone, Three Boys Formation, Perseverance Jaspilite, Mars Greenstone, Hill 50 Jaspilite, Havelock Greenstone and Saturn Formation. Within these formations fine-grained sediments, volcanic rock and jaspilite are conformably interbedded. They were probably deposited within an eugeosyncline which itself provided a source for clastic and chemical material. Instability during deposition has caused: buried valley structure; buried hill structure; rapid thickening of units; slump structures and brecciation. Ripple marking and cross lamination in siltstone and calcareous nodules in jaspilite were used to determine sequence.

During intrusion of granite the group was folded, metamorphosed and fractured. The intrusion of porphyry and quartz blows followed and was accompanied by mineralization. Later, during taphrogenesis, dolerite was intruded.

Erosion has since peneplaned the area. There is evidence of a more rugged topography before lateritization in the Tertiary.

Introduction

Boogardie is situated approximately 3 miles N. 65° W. from Mount Magnet and approximately 300 miles NNW. of Perth, Western Australia. Gold-bearing ore is being produced at the present time (1958) from two mines at Boogardie. These are the Hill 50 and Hill 50 Eclipse gold mines. To the end of 1956 the Hill 50 gold mine had crushed 982,105.90 tons for a return of 448,601.75 fine ounces of gold.

The Archean rocks of the district are steeply dipping and consist of lavas, sedimentary greenstones and jaspilites, probably deposited in an eugeosyncline. A stratigraphic subdivision of these rocks has been made and their proposed nomenclature is set out herein.

General Stratigraphy

The interbedded lavas and sediments of the Mount Magnet district are tightly folded and intruded by granite. They fall within the Yilgarn Geosyncline of Prider (1952) and are consequently correlated with the Older Greenstone Phase of Prider (1948).

The distribution of rocks near Boogardie is shown in Fig. 1. Two major stratigraphic units have been delineated—the Lennonville Beds and the Boogardie Group.

The Lennonville Beds

The name Lennonville Beds is proposed herein for the sequence of greenstones, jaspilites, cherts and (?) conglomeratic quartzites, of Pre-cambrian age, bounded above by the Boogardie Group and below by an unknown thickness of sediments.

The Lennonville Beds to the north of the Hill 50 gold mine are composed in stratigraphic order of the following lithologies:

4. 2,500-7,500 feet of amphibolite, chloritized quartz dolerite and chlorite schist, with thin (6 ins.-1 foot) jaspilite beds.
3. 45 feet ± of quartzite, conglomerate, and conglomeratic quartzite.
2. 50 feet ± of chert.
1. 90 feet ± of interbedded greenstone and jaspilite with thin cherty members, grading in the upper 30 feet to jaspilite with rare cherty members.

The jaspilites and cherts are coarser in grain size than those nearer Boogardie. Stylolitic seams parallel the bedding in the cherts, and adjacent to the seams recrystallization is marked. Lateral gradation of interbedded chert and jaspilite is best explained by a sedimentary facies change for the following reasons:—

There is no apparent change in thickness when jaspilite changes to chert; there is rapid change in iron content and close association of jaspilite with chert; stylolites in banded iron formations generally mark an increase in iron content, not a complete absence of this element.

The stratigraphic position of the quartzite, (?) conglomeratic quartzite and (?) conglomerate is in doubt, but it is thought that they are a conformable sedimentary sequence within the Lennonville Beds. They vary lithologically from conglomeratic quartzite to even-grained quartzite. Under the microscope these rocks show little evidence of the fragmental texture seen in hand-specimen. Large fragments in the conglomerate or breccia are similar to the matrix, being distinguished from it only by a lack of ferruginous cement. Bedding and the recrystallized nature of the rock suggest it is conformable with the jaspilites. However, some specimens resemble the superficial deposits known elsewhere in Western Australia as "billy."

It may be considered that the conglomeratic quartzite and even-grained quartzites are conformable with the jaspilites and that a superficial deposit was formed on these rocks in comparatively recent times. This explanation is accepted until the problem of the two rock types of roughly similar composition but different metamorphic grade can be solved.

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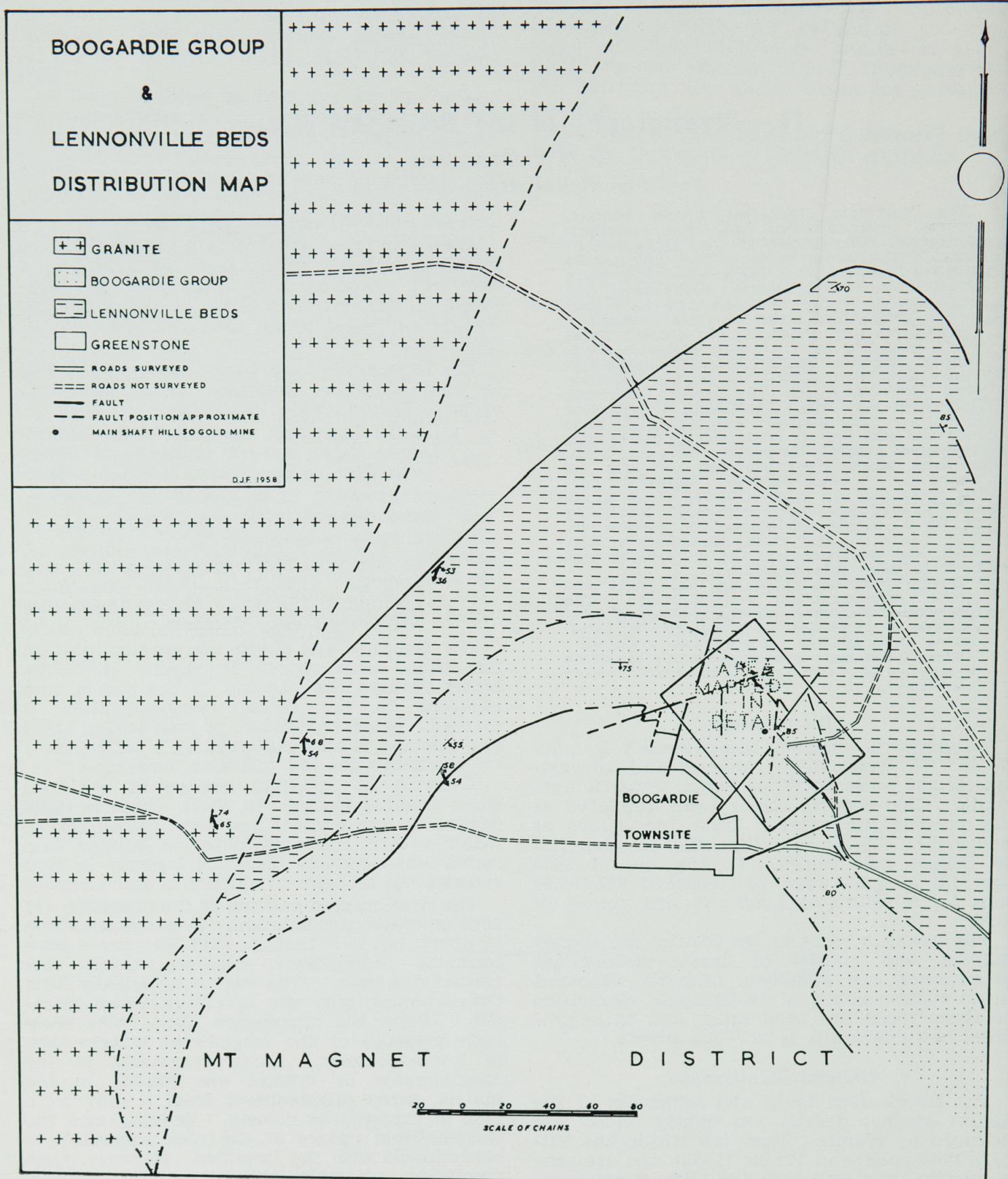


Fig. 1.—Distribution map (compiled from aerial photographs and traverses on foot).

Chert, jaspilite and quartzite are the basal rocks of the Lennonville Beds; above the base there is a considerable thickness of greenstone, with minor jaspilite beds. The greenstone is dominantly amphibolite and chloritized quartz dolerite in fresh outcrop. Closer to the Boogardie Group the greenstones are highly weathered schists.

The Boogardie Group

The name Boogardie Group is proposed herein for part of the sequence of sedimentary and conformable igneous rocks in the south-plunging syncline about Boogardie. The group has been traced in outcrop from two miles south-east of the Hill 50 gold mine, through the trough of the fold (adjacent to the Hill 50 gold mine), to a point four miles south-west of Hill 50 where the sediments abut against the granite. The strata which dip steeply have an average thickness of 4,000 feet.

The formations within the Boogardie Group are presumed to be Archean in age. The following is a summary of the sequence (Fig. 2).

Boogardie Group.—Jaspilites and greenstones of Archean age conformably contained in the greenstones of the Mount Magnet district and composed of the following nine formations, in stratigraphic order:

9. Saturn Formation.—A sequence of jaspilites and greenstones including bedded sericite-carbonate-quartz-chlorite schist. Thickness 702 feet \pm .

8. Havelock Greenstone.—Fine-grained chloritized quartz dolerite underlying a six-inch jaspilite member. Thickness 17-40 feet.

7. Hill 50 Jaspilite.—Jaspilite. Thickness, (?) 50-80 feet.

6. Mars Greenstone.—A sequence of jaspilites and greenstones including bedded magnetite-bearing biotite-quartz-chlorite schist, chloritized quartz dolerite and plagioclase-quartz-carbonate-chlorite rock. Thickness, 140-280 feet.

5. Perseverance Jaspilite.—Jaspilite with calcitic nodules. Thickness, 20-38 feet.

4. Three Boys Formation.—Jaspilites and greenstones including sericite-quartz-magnetite-carbonate-chlorite schist and plagioclase-bearing sericite-magnetite-carbonate-quartz-chlorite rock. Thickness, 250-330 feet.

3. Mount Magnet Greenstone.—A sequence of minor jaspilites and greenstones including banded magnetite-plagioclase-carbonate-chlorite rock and quartz-carbonate-sericite-chlorite rock. Thickness, 300-710 feet.

2. Jupiter Jaspilite.—Dominantly jaspilite carrying calcitic nodules, and interbedded with greenstone lenses. Thickness, 4-30 + feet.

1. Poverty Flat Formation.—Dominantly magnetite-quartz-carbonate-chlorite schist with minor magnetite-sericite-quartz-chlorite schist and characterized by four or five interbedded 6 in. to 1 ft thick jaspilite members. Thickness, 1,033 \pm feet.

Intrusive into the Lennonville Beds and the Boogardie Group are various quartz-feldspar porphyries, granite, quartz blows and dolerite, which will be dealt with below.

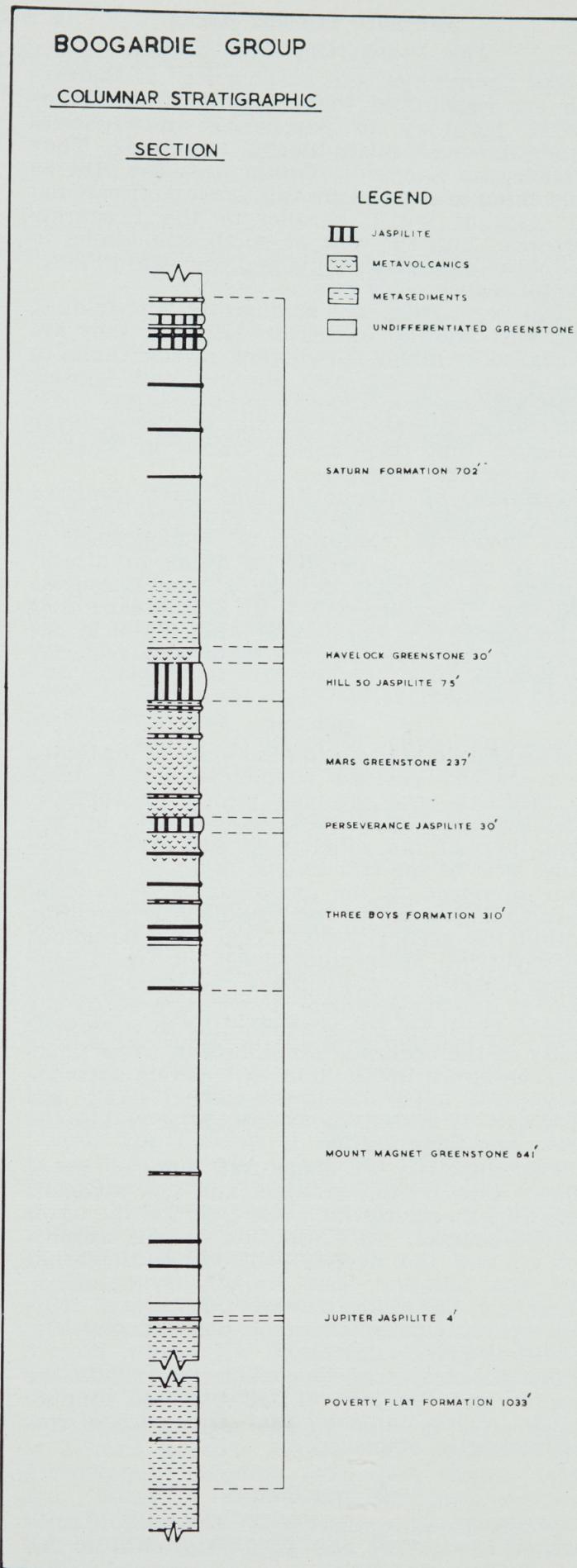


Fig. 2.

Intrusive Igneous Rocks

The Porphyritic Dyke Rocks

The "porphyries and porphyrites" of Boogardie are hypabyssal rocks ranging from leucodacite porphyry to porphyritic micro-diorite (andesite) and micro-diorite (andesite). They intrude the Boogardie Group near the Hill 50 gold mine and trend in two general directions: 30° east of north, parallel to the Boogardie "Breaks," and 50° west of north, subparallel to the strike of the sediments and the "Main Fault" of the Hill 50 gold mine.

The porphyrites are dominantly post-folding, and post-faulting intrusives, although they are displaced by minor flat-dipping reverse faults in the mine, and are also sheared and jointed. Flow alignment of chlorite pseudomorphs (possibly after hornblende) in one porphyrite dyke indicates that they were intruded in what is now a vertical direction.

Intrusion of porphyrite may have occurred over a considerable period, as Finucane (1953, p. 232) shows the "Main Fault" (which itself is said to contain a porphyrite filling in places) cutting the porphyrite filling the Boogardie "Breaks." Finucane (1953, p. 232) claims that a little gold has occasionally been found in the porphyry, so that they are tentatively regarded as pre-ore.

Granite

The granite varies between a fine- to medium-, even-grained gneissic adamellite and a fine- to medium-, even-grained massive adamellite. The igneous contact with amphibolites on the west limb of the syncline is well-exposed two miles west of the Hill 50 gold mine. The lineation developed in the amphibolites is identical with that in some of the amphibolitic xenoliths within the granite itself. There are numerous cross-cutting aplongranite dykes in the greenstone adjacent to the contact. In these a foliation is developed which is not parallel to the dyke trend itself but is subparallel to the schistosity of the enclosing amphibolites. The foliation developed in the granite, trending approximately 20°, is parallel to the contact and to the direction of elongation of xenoliths of amphibolite and metajaspilite.

The similarity of structural features noted above, both in the granites and the adjacent amphibolitic schists indicates that the intrusion of the granite, the formation of the amphibolites, and the development of the lineation and the foliation were broadly synchronous. Therefore, the writer believes the regional folding was caused by, and took place during, the period of granite intrusion.

The absence of hornblende xenocrysts in the granite and the lack of feldspathized amphibolitic schists indicate that the granite was magmatically emplaced.

Quartz Blows

Quartz blows concordantly and discordantly intrude the schists and gneissic granite of the Mount Magnet district.

The quartz "reefs" are usually poorly mineralized. Gold, pyrite, stibnite, cervantite, stibiconite, scheelite, psilomelane, pyrolusite and

fuchsite were noted by Jutson many years ago and tourmaline occurs in many of them. They are apparently lenticular, rarely greater than 10-15 feet wide, and some may be traced for several hundreds of feet along their strike. In the Boogardie district they are rarely longer than 20-30 feet.

Dolerite

A quartz dolerite dyke intrudes the Boogardie Group at the Hill 50 gold mine. The dyke has an east-west trend and maintains a constant width of 18 in. to 2 feet.

The absence of alteration in this rock, which intrudes chloritic schists, chloritized quartz dolerite and most probably partially altered porphyrite dykes, indicates that it is later in age than any of them and the lack of alteration and the inclusion of a xenolith of pyrrhotized jaspilite, demonstrates that the dolerite is post-ore in age. Structurally, it follows a trend foreign to the normal mine structures.

Metamorphism

The "greenstones" in the vicinity of the Hill 50 gold mine have developed minerals typical of the greenschist facies of metamorphism. Two and a half miles west-north-west of the mine the "greenstones" are intruded by granite and their mineral content is more typical of the albite-epidote or lower amphibolite facies of metamorphism.

Amphibole has been proven to develop in rocks originally of igneous character and also in rocks originally of sedimentary character without evidence of directional stresses. The resultant amphibolites are probably metasomatic in origin and occur in areas of low grade metamorphism as well as in areas of moderate grade metamorphism.

Superficial Deposits

Superficial deposits of conglomerate, travertine, laterite and alluvium are the products of weathering and erosion of the older rocks of the region.

Stratigraphy of the Boogardie Group

Within this section will be found the definition, facies variations, geographic distribution and petrography of the formations of the Boogardie Group. The petrography is limited to the component greenstones. The jaspilites show little variation and their petrographic description will be found in the following section under Petrology.

The Boogardie Group (Fig. 2) consists of nine formations with the following bottom-to-top sequence:—

Poverty Flat Formation

Poverty Flat is the name of an area approximately two miles south-east of the Hill 50 gold mine, and characterized by a number of thin jaspilite bars along which fault intersections have yielded occasional bonanzas.

Definition.—The Poverty Flat Formation is defined as that sequence of minor jaspilite bars and chert-carbonate-chlorite schists, which lies between and is bounded by the Lennonville Beds and the Jupiter Jaspilite.

TABLE I

Facies variations in the Jupiter Jaspilite

| G.M.L. 1505M | G.M.L. 1361M | G.M.L. 1389M and 1478M | (a) | G.M.L. 1480 | (b) |
|---------------------------|---------------------------|------------------------------|--|--|-----|
| | | | North end of area mapped | | |
| | | | South-east corner | Centre | |
| 4' jaspilite with nodules | 4' jaspilite with nodules | 3'-4' jaspilite with nodules | 10' jaspilite with two minor greenstone lenses 6" to 1' thick | 6' jaspilite with nodules 15' greenstone 2' 6" jaspilite with nodules 9' greenstone 18" jaspilite with nodules | |

The formation is typically developed east-south-east of the Hill 50 gold mine between surface co-ordinates* 13660E 11100N and 12524E 11230N.

The type locality contains no unweathered outcrop. The extent of faulting could not be determined to fine limits and hence the thickness given is approximate only (assuming dips close to vertical).

Unweathered samples of the formation from the Jupiter mullock dump, 12700E 13100N, were compared with weathered material from the surface, in both hand specimen and thin section—thus permitting partial determination of the greenstone type.

A description of the relative positions of jaspilites and the thicknesses of the component units is now given.

Jupiter Jaspilite

Poverty Flat Formation:

| Unit | Thickness Feet |
|---|-------------------------------|
| 10—Greenstone; dominantly chert-carbonate-chlorite schist, occasionally massive chert-carbonate-chlorite rock | 14 |
| 9—Jaspilite | 1 ¹ / ₂ |
| 8—Greenstone, probably chert-carbonate-chlorite schist and massive chert-carbonate-chlorite rock | 846 |
| 7—Jaspilite | 1 ¹ / ₂ |
| 6—Greenstone | 40 |
| 5—Jaspilite | 1 ¹ / ₂ |
| 4—Greenstone | 36 |
| 3—Jaspilite | 1 ¹ / ₂ |
| 2—Greenstone | 95 |
| 1—Jaspilite | 1 ¹ / ₂ |
| Estimated total thickness: 1033 | |

Lennonville Beds

Geographic distribution.—The Poverty Flat Formation persists as the basal unit of the Boogardie Group throughout most of its extent. Variations in thickness were not measured.

Lithology.—The dominant greenstone type is a chert-carbonate-chlorite schist. In hand-specimen the unweathered rock is dark green but with abundant light-coloured irregular shreds of carbonate and chert. It weathers to a yellow-brown rock in which shreds of chert are still visible in a matrix of limonite. Bedding is weakly developed and rarely visible in surface outcrops. Schistosity is frequently well-

developed close to quartz blows, and runs parallel to the dip and strike of the formation. Elsewhere the rock may appear massive.

Jupiter Jaspilite

Jupiter is the name of G.M.L. 1361M. Mining operations on this lease were largely carried out in the Jupiter Jaspilite.

Definition.—The Jupiter Jaspilite is defined as that jaspilite with greenstone lenses which lies between the Poverty Flat Formation and the Mount Magnet Greenstone (see Fig. 2). The formation is typically developed on G.M.L. 136M Jupiter, near the Jupiter mullock dump at 12780E 13160N.

The jaspilite consists of clear continuous black, brown and grey bands approximately 0.5 cm apart.

Good outcrop and the presence of numerous calcite nodules allowed ready recognition of the formation and accurate estimation of thickness along its length.

Geographic distribution.—The formation is well-developed in the area mapped. In the Hill 50 gold mine (414' level) a four-foot jaspilite containing calcitic nodules is exposed in the main cross-cut and is thought to be the Jupiter Jaspilite. The formation has not been traced outside the limits of the area mapped in detail.

Petrography.—Two rock types are found in the Jupiter Jaspilite—these being greenstone and jaspilite. The greenstone outcrops on G.M.L. 1480M. The outcrop of highly weathered rock is good and shows a marked, nearly vertical, fracture cleavage trending approximately north-east. The weathered outcrop is a medium yellow-brown colour without visible bedding. Its nature is indeterminate.

Mount Magnet Greenstone

Mount Magnet is the name of the township around which the Boogardie district mining operations now centre. It is situated 352 miles by road north-east of Perth.

Definition.—The Mount Magnet Greenstone is defined as that sequence of jaspilites and greenstones, including chloritized banded feldspar porphyry and quartz-carbonate-sericite-chlorite rock, lying between and bounded by the Jupiter Jaspilite and the Three Boys Formation.

The type section is on G.M.L. 1361M Jupiter, between co-ordinates 12760E 13070N and 12130E 13000N. Outcrops of greenstone are poor, being

*Note: Co-ordinates shown thus: 13660E 11100N refer to surface co-ordinates expressed in feet. To obtain Hill 50 gold mine co-ordinates, expressed thus 13646E, 11075N, apply the transformation E + 14 = E', N + 25 = N', where E, N are mine co-ordinates and E', N' are surface co-ordinates.

highly weathered and lateritized. Jaspilites of this formation generally outcrop well, but because of large areas of poorly outcropping greenstones and the faulted nature of the type section, the indicated total thickness is approximate only.

The type section in stratigraphically descending order is given immediately below.

Three Boys Formation Mount Magnet Greenstone:

| Unit | | Thickness Feet |
|--|------|-------------------|
| 9—Greenstone | .... | 360 |
| 8—Jaspilite | .... | 4 |
| 7—Greenstone | .... | 130 |
| 6—Jaspilite | .... | 2 |
| 5—Greenstone | .... | 44 |
| 4—Jaspilite | .... | 4 |
| 3—Greenstone | .... | 70 |
| 2—Jaspilite | .... | 1 |
| 1—Massive, fine-grained purplish-red, highly weathered greenstone | .... | 26 |
| Estimated total thickness, Mount Magnet Greenstone | .... | 641 |

Jupiter Jaspilite

Geographic distribution.—The Mount Magnet Greenstone persists throughout the area mapped in detail. Unit 9 of the type section thins from a thickness of 500' + in the south of the area to almost 140 feet at the junction of G.M.L.'s 1389^M and 1435^M. Thus the distinctive width of greenstone which marks the top of this formation in the south becomes less distinctive further north and the precise upper limit is more difficult to recognize.

On G.M.L. 1480^M penecontemporaneous tectonics seem to be indicated in both this formation and the underlying Jupiter Jaspilite, by the presence of a buried hill-like structure, by the greenstone lenses appearing in the Jupiter Jaspilite and by intraformational folding suggestive of slumping. Should this evidence indicate tectonic instability, the rapid thickening and thinning of beds is readily explained as a broader consequence.

Facies variations.—Unit 9 varies in the manner indicated above. Jaspilite members of this formation are variable in both thickness and position. For example one jaspilite member changes in thickness from 4' to 10' between G.M.L. 1435^M and G.M.L. 1480^M. For this reason, certain correlation of individual jaspilite members from one fault block to the next is difficult.

Three Boys Formation

Three Boys is the name of G.M.L. 1322^M, a lease about one half-mile south-east of the Hill 50 gold mine.

Definition.—The name Three Boys Formation is here proposed for the sequence of jaspilites and greenstones lying between and bounded by the Mount Magnet Greenstone and the Perseverance Jaspilite.

The type section is exposed west of the Hill 50 main shaft, between co-ordinates 11044E 12888N and 11350E 13000N on G.M.L. 1438^M (Mars) and G.M.L. 1356^M.

Because of the highly weathered nature of the fine-grained greenstone at the surface, no specimens were taken from the type locality. The lithologies described below are identified from the workings of the Hill 50 gold mine.

The following is a description of the type section in stratigraphically descending order.

Perseverance Jaspilite Three Boys Formation:

| Unit | Thickness Feet |
|---|-------------------|
| 14—Fine - grained plagioclase - magnetite - carbonate - quartz - chlorite - sericite schist and moderately massive fine-grained dark greenish grey, feldspar-bearing sericite-iron ore-carbonate-quartz-chlorite rock | 40 |
| 13—Jaspilite | 2 |
| 12—Quartz-magnetite-carbonate-chlorite schist | 60 |
| 11—Jaspilite | 2 |
| 10—Greenstone | 30 |
| 9—Jaspilite | 6 |
| 8—Greenstone | 45 |
| 7—Jaspilite | 3 |
| 6—Greenstone | 13 |
| 5—Jaspilite | 5 |
| 4—Greenstone | 9 |
| 3—Jaspilite | 1 |
| 2—Greenstone | 85 |
| 1—Jaspilite | 4 |

Total estimated thickness: 310

Mount Magnet Greenstone

Geographic distribution.—The Three Boys Formation persists throughout the area mapped in detail, and beyond to the south-east. To the north-west of the area the base of the Three Boys Formation is difficult to distinguish from the top of the Mount Magnet Greenstone.

Facies changes.—The thickness and position of the various units of this formation change in such a manner that their correlation from fault block to fault block is uncertain. Within the area mapped in detail the formation as a whole converges from 500' thickness in the north-west to approximately 250' thickness in the south-east. Over the lateral distance of half-a-mile of this convergence individual jaspilite members thicken as greenstone members become thinner.

Perseverance Jaspilite

Perseverance is the name of G.M.L. 1505^M in which the main workings have been in the formation here defined as the Perseverance Jaspilite.

Definition.—The name Perseverance Jaspilite is proposed herein for that jaspilite lying between and bounded by the Three Boys Formation and the Mars Greenstone.

The type section is on G.M.L. 1438^M (Mars) at co-ordinate 11116E 12744N. At this locality it is a banded brown, grey and black rock containing sparse cavities near its base, marking the position of leached or weathered calcitic nodules. It is thirty feet thick.

Geographic distribution and facies changes.—The Perseverance Jaspilite is readily recognizable throughout its length in the area mapped in detail and beyond to the south-east. Below is a Table showing variations in thickness of this formation within a lateral extent of three-quarters of a mile.

TABLE II

| Locality | Thickness (feet) |
|--------------|---------------------|
| G.M.L. 1287M | 24 |
| G.M.L. 1323M | 40 |
| G.M.L. 1282M | 38 |
| G.M.L. 1438M | 30 |
| G.M.L. 1435M | 30 |
| G.M.L. 1533M | 26 |

Underground, the Perseverance Jaspilite may be seen in the Perseverance workings at a depth of 313' and in the Hill 50 gold mine, 1,060' level, at the east end of the new east crosscut.

Mars Greenstone

Mars is the name of G.M.L. 1438M, a lease approximately 500 feet west of the Hill 50 main shaft.

Definition.—Mars Greenstone is the name given to the sequence of jaspilites and greenstones lying between and bounded by the Perseverance Jaspilite and the Hill 50 Jaspilite.

The type section is defined underground on the 313' level of the Hill 50 gold mine and the Perseverance workings. However, due to poor structural data exposed in the underground workings, thicknesses of the strata are incompletely known and have been adopted from surface exposures near the south end of G.M.L. 1323M.

The following is a description of the section in stratigraphically descending order.

Hill 50 Jaspilite

Mars Greenstone:

| Unit | Thickness Feet |
|--|-------------------|
| 7—Magnetite- and quartz-bearing biotite-carbonate-chert-chlorite rock with distinct relict lamination and small-scale cross-lamination | 10 |
| 6—Jaspilite | 6 |
| 5—(?) Bedded, magnetite- and quartz-bearing, carbonate-chert-chlorite rock, fine-grained ilmenite-bearing plagioclase-quartz-chlorite rock, and (?) medium - grained chlorite - carbonate - albite rock | 55 |
| 4—Jaspilite | 8 |
| 3—Magnetite - carbonate - quartz - plagioclase-chlorite rock (20' +), magnetite-bearing plagioclase-quartz-carbonate-chlorite schist, (?) ilmenite-plagioclase-chlorite rock and (?) ilmenite - bearing quartz - chloritized plagioclase-chlorite rock | 112 |
| 2—Jaspilite | 6 |
| 1—Fine-grained cherty quartz-plagioclase-chlorite rock | 40 |
| Total estimated thickness: | 237 |

Perseverance Jaspilite

Distribution.—The Mars Greenstone may be traced through the area mapped in detail, and to the south-east; its extension to the north-west is not known. The stratigraphic sequence is broadly similar from G.M.L. 1287M, through G.M.L. 1323M, G.M.L. 1282M, to G.M.L. 1438M. On G.M.L.'s 1435M and 1536M, the formation boundaries may be traced, but, due to heavy lateritization and poor outcrop within the formation, little of the actual sequence is known.

Approximate local thicknesses of the formation are shown in Table III. They indicate convergence from south-east to north-west.

TABLE III

| Locality | Thickness (feet) |
|--------------|---------------------|
| G.M.L. 1287M | 200 |
| G.M.L. 1323M | 230 |
| G.M.L. 1438M | 220-180 |
| G.M.L. 1435M | 240 |
| G.M.L. 1536M | 130 |

Hill 50 Jaspilite

Hill 50 is the name of G.M.L. 1282M, on which the upper levels of the Hill 50 gold mine are situated. At the time of writing, ore shoots were being worked within the Hill 50 Jaspilite.

Definition.—Hill 50 Jaspilite is the name given to that jaspilite lying between and bounded by the Mars Greenstone and the Havelock Greenstone. The type section is exposed on the 613' level of the Hill 50 gold mine, where a true thickness of 75' is exposed.

Distribution and thickness variations.—The Hill 50 Jaspilite, because it is by far the thickest jaspilite in the Boogardie Group, serves as a useful marker bed. It may be traced from fault block to fault block in the area mapped in detail. Its extension, north-west and west of this area is not known, but it may be traced to the south-east for at least one mile.

Approximate thicknesses of the formation are shown in Table IV.

TABLE IV

| Locality | Thickness (feet) |
|--------------|--|
| G.M.L. 1287M | 70 |
| G.M.L. 1323M | 77 |
| G.M.L. 1282M | ? 50-75 |
| G.M.L. 1438M | 65-80 |
| G.M.L. 1536M | 75 true width X-cut within the Hill 50 Central workings. |

Havelock Greenstone

Havelock is the name of G.M.L. 1287M on which this formation outcrops.

Definition.—Havelock Greenstone is the name given to the chloritized basalt and minor jaspilite lying between and bounded by the Hill 50 Jaspilite and the Saturn Formation.

The type section is exposed on the 313' level of the Hill 50 gold mine at which location the formation is between 25' and 30' thick.

The following is a description of the type section.

Saturn Formation

Havelock Greenstone:

| Unit | Thickness Feet |
|-------------------------------------|-------------------------------|
| 3—(Top) Jaspilite | $\frac{1}{3}$ |
| 2—Chloritized basalt | 25-30 |
| 1—(Bottom) Chlorite schist | $\frac{1}{3}$ |
| Total estimated thickness = approx. | 30 |

Hill 50 Jaspilite

Distribution and thickness variations.—The Havelock Greenstone is traceable through G.M.L.'s 1462^M, 1287^M, 1323^M, 1282^M (subsurface) to G.M.L. 1438^M. Its continuation on G.M.L. 1536^M is obscured by extensive lateritization.

Approximate thicknesses for each locality are given in Table V.

TABLE V

| Locality | Thickness (feet) |
|--------------------------|------------------|
| G.M.L. 1462 ^M | 22 |
| G.M.L. 1287 ^M | 24 |
| G.M.L. 1323 ^M | 20 |
| G.M.L. 1282 ^M | 30 (subsurface) |
| G.M.L. 1438 ^M | 19 |

Underground in the workings of the Hill 50 gold mine, the formation is exposed on all levels—its thickness reaches a maximum of 38' on the 1304' level.

Saturn Formation

Saturn is the name of G.M.L. 1457^M. An open cut, known as the Saturn open cut, has been worked in the jaspilite members of this formation.

Definition.—Saturn Formation is the name proposed herein for that sequence of jaspilite and greenstone directly overlying the Havelock Greenstone, and bounded above by a considerable though unknown thickness of greenstone, apparently devoid of jaspilite members.

The type section lies between surface coordinates 10512E 11190N and 11230E 11130N. In the type section, the high degree of faulting and porphyry intrusion, coupled with a generally poor outcrop of both jaspilite and greenstone, render interpretations of the geology and thickness estimations inexact.

The figure given below (702') is far less than that observed in other fault blocks, and must be accepted with reservations.

The following is a description of the section in stratigraphically descending order.

Saturn Formation:

| Unit | | | | | | Thickness Feet |
|---------------------------------|-----|-----|-----|-----|-----|-------------------|
| 14—Jaspilite | ... | ... | ... | ... | ... | 8 |
| 13—Greenstone | ... | ... | ... | ... | ... | 27 |
| 12—Jaspilite | ... | ... | ... | ... | ... | 20 |
| 11—Greenstone | ... | ... | ... | ... | ... | 6 |
| 10—Jaspilite | ... | ... | ... | ... | ... | 6 |
| 9—Greenstone | ... | ... | ... | ... | ... | 3 |
| 8—Jaspilite | ... | ... | ... | ... | ... | 27 |
| 7—Greenstone | ... | ... | ... | ... | ... | 68 |
| 6—Jaspilite | ... | ... | ... | ... | ... | 3 |
| 5—Greenstone | ... | ... | ... | ... | ... | 85 |
| 4—Jaspilite | ... | ... | ... | ... | ... | 5 |
| 3—Greenstone | ... | ... | ... | ... | ... | 94 |
| 2—Jaspilite | ... | ... | ... | ... | ... | 4 |
| 1—Greenstone | ... | ... | ... | ... | ... | 340 |
| Total estimated thickness = 702 | | | | | | |

Havelock Greenstone

Geographic distribution and thickness variations.—The Saturn Formation may be traced from aerial photographs, throughout the entire

examined length of the Boogardie Group. It appears to thin from approximately two thousand feet thickness, several miles south-east of Boogardie, to approximately seven hundred feet in the type section. Further north-west from Boogardie, it firstly thickens and then slowly thins until the junction with granite four miles west of the Hill 50 gold mine.

Thickness variations of individual members may be observed in units 8 to 14, which have thickened considerably on G.M.L. 1487^M, (west of the Mars lease G.M.L. 1438^M) from their thicknesses in the type area further south-east.

Lithology.—The typical rock type is a sericite-carbonate-chert-chlorite schist cut by innumerable carbonate-quartz veinlets which run sub-parallel to the foliation. On the 820' and 1,060' levels of the Hill 50 gold mine the unit is in part conglomeratic, especially near its base. One detrital fragment, about six inches in diameter, is roughly circular in cross-section and is composed of a white kaolin-like material regardless of being enclosed in unweathered schist on the 1,060' level. Other fragments (e.g. of quartz) are smaller (about 0.5 inch in diameter) and roughly circular in cross-section. Clear, closely spaced bedding indicates a sedimentary origin for this rock. It weathers to a yellow-brown colour.

The lithologies of the overlying greenstone units are uncertain but are believed to include both schists containing variable amounts of quartz, biotite, sericite, chlorite and carbonate and a chloritized medium-grained porphyritic and trachytic rock composed dominantly of albite and chlorite with minor iron ore.

Petrology

Within the Boogardie Group, fine-grained sedimentary and igneous rocks and jaspilites occur in a conformable eugeosynclinal sequence. Metamorphism has so altered many of the rocks that their origin is indeterminate. Others are igneous in origin and probably lavas or sills; others are sedimentary in origin. Working with those rocks whose origin is least in doubt this section will deal with petrological features of the jaspilites and igneous and sedimentary greenstones which help to construct a picture of their depositional environment.

Flow Lavae

Units 1, 3, and 5 of the Mars Greenstone, the Havelock Greenstone, and parts (specimen 39515*) of the Mount Magnet Greenstone are probably flow lavas. They are generally massive and jointed and have suffered chloritization, sericitization and carbonation. Undoubted porphyritic texture is apparent in most specimens. The feldspars vary from albite Ab₉₅ to oligoclase Ab₇₃ indicating all stages of alteration from a more calcic plagioclase. The refractive indices of chlorite are constant at 1.622 ± .002 (6 specimens), identifying the variety as either diabantite or ripidolite.

Alteration of plagioclase to sericite, chlorite, quartz, carbonate, albite and rare epidote has taken place in many cases. These changes are

*Specimen numbers refer to specimens held at the University of Western Australia.

due to the instability of calcic plagioclase under greenschist facies metamorphism and in some cases are due to instability of the feldspar in the presence of alkaline hydrothermal solutions.

The data available suggest that the rocks were basic or intermediate lavas and/or sills such as basalt or andesite. These data are:—fine grain size; porphyritic texture; gradation of feldspars from albite to calcic oligoclase; relict basalt textures and general absence of normal crystalline quartz (microcrystalline quartz may be quite abundant). Anhedral quartz in these rocks may or may not be of primary origin. Where it is present it is not possible to ascribe acid or basic character to the original rock, even when a flow lava origin is admitted.

Sedimentary Greenstones

Sedimentary greenstone comprises much of the greenstone in the Poverty Flat Formation; unit 5 in the Mars Greenstone; unit 7 of the Mars Greenstone, and the base of unit 1 in the Saturn Formation.

All these rocks are fine-grained, with closely spaced bedding. The mineralogy is simple; microcrystalline quartz, carbonate, chlorite, sericite, magnetite, biotite and minor (?) detrital quartz in varying proportions. Plagioclase is absent.

Unit 7 of the Mars Greenstone has been studied in detail and the following sedimentary structures have been found:—

Well-developed closely spaced lamination (Fig. 3).

Small scale cross-lamination marked by fine-grained magnetite and biotite (Fig. 3).

Ripple markings and associated scour and fill structure (Fig. 4).

Small scale slumping.

In one locality an erratic of jaspilite about 18" in diameter.

In addition the following minerals have been found to be concentrated in certain laminae; calcite, biotite, magnetite, (?) detrital quartz, microcrystalline quartz, and chlorite. Of these, magnetite, biotite and possibly chlorite have

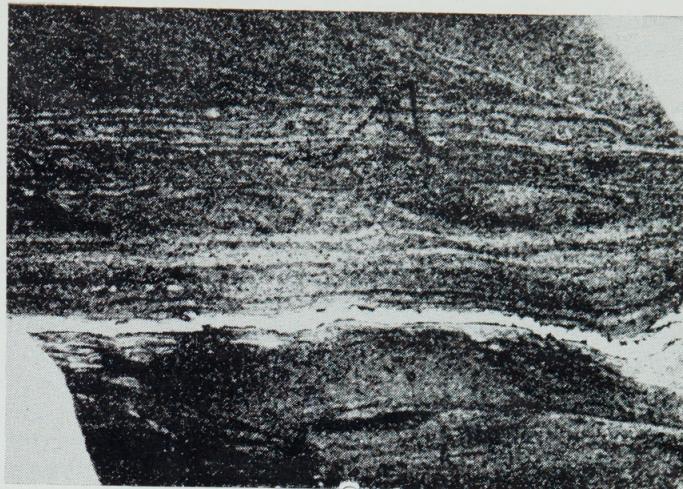


Fig. 4.—Ripple marking and associated scour and fill structure in unit 7 of the Mars Greenstone (specimen 33546). Ordinary light X2.

been derived from heavy minerals, originally sorted by physical processes. Carbonate, where concentrated in a single lamina appears to have been chemically precipitated although one specimen does show doubtful evidence of detrital origin for the carbonate. The intimate admixture of microcrystalline quartz and chlorite often with carbonate, indicates co-deposition. The chert and carbonate are believed to be largely chemical in origin while the chlorite is probably derived from pelitic detritus.

The rock resembles the result of a combination of slow chemical sedimentation of carbonate and (?) quartz, with additions of very fine terrestrial material, and fine volcanic ash; the latter probably altered during diagenesis to silica and clay minerals. Slight current action over a relatively flat depositional interface is indicated by small-scale cross lamination, ripple marks and associated scour and fill structures. This process and minor slumping would fill any major irregularities in the depositional interface and slumping appears to be the best explanation for the jaspilite erratic two feet from the base of the unit.

The presence of conglomeratic lenses in unit 1 of the Saturn Formation implies a shallow-water environment and this may be extrapolated to suggest a quiet shallow environment for the interbedded fine-grained sediments.

The deposition of the sedimentary greenstone was probably accompanied by contemporary vulcanism with the addition of ejectamenta (erratic boulder in unit 1 of the Saturn Formation) and by slumping due to seismic stimuli.

Jaspilite

Definition.—According to Holmes (1928, p. 127) jaspilite is "A term applied to rocks composed of interbanded layers respectively rich in silica (quartz or chalcedony) and iron oxides (magnetite, haematite, etc.). The chert-like bands have a red colour owing to the inclusion of flakes of haematite. Variable amounts of ferruginous amphiboles are generally present, and the rocks are not only conspicuously banded but are often contorted and brecciated."

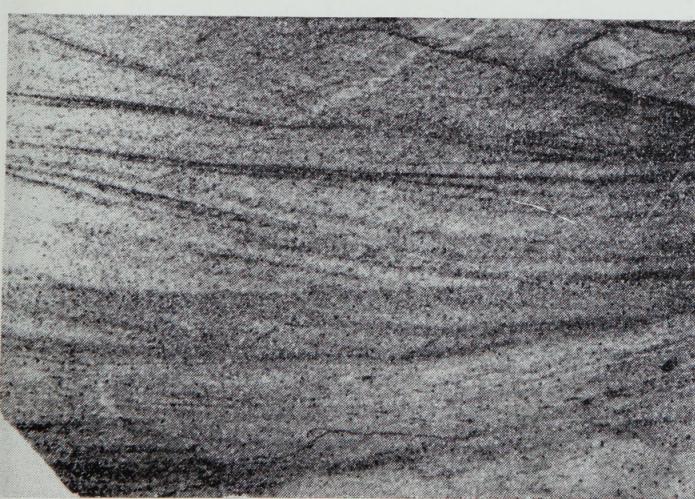


Fig. 3.—Cross-lamination in unit 7 of the Mars Greenstone (specimen 33544). Ordinary light X2.

Miles (1941, p. 15) suggests "that this term jaspilite might be extended slightly in meaning, to include certain black and white varieties of similar banded rock which, in many of the Western Australian goldfields, show close field relations with, and occasionally grade into, the red banded kind."

At depths of 600' and greater the jaspilites of the Boogardie Group contain bedded calcite, often in an amount sufficient to designate a small specimen as a banded magnetite-calcite rock. Furthermore, under conditions of greenschist facies metamorphism, minor chlorite is developed rather than amphibole. Evidence is brought forward below to demonstrate that banded calcite-magnetite-chert rocks become silicified and oxidized at the surface to banded haematite and magnetite-chert rocks—true jaspilites under the definition.

Petrologic Description.—Specimen 39575 (11616E, 12433N, 613' level) is a specimen of poorly auriferous jaspilite from the type locality of the Hill 50 Jaspilite.

In hand specimen it is a black and grey, clearly banded rock composed of alternating iron-rich, silica-rich, or carbonate-rich bands, 10 mm to 2 mm in width. Intraformational brecciation thought to be due to slumping, is evident in hand specimen. Minor sulphide mineralization occurs in small cross-cutting fractures and along favourable bands. The specimen has a specific gravity of 3.27.

In thin section the banding is seen to be prominent. Graded bedding or cross bedding is not present, although there is a variation in grain size of the microcrystalline quartz in different bands.

The carbonate, magnetite and quartz are bedded in a sedimentary manner. There is in this specimen and in all others examined from the underground workings a distinct tendency for the carbonate to occur in the same bands as magnetite. Minor fractures traverse the slide without any continuity or apparent displacement. They contain microcrystalline quartz where they cross chert bands and carbonate where they cross carbonate- and magnetite-rich bands, although no fracture was traceable from a chert band to a carbonate-rich band.

Constituent minerals are microcrystalline quartz (45%), iron ores (30%), carbonate (25%), and minor chlorite (<1%).

Microcrystalline quartz is composed of anhedral grains 0.040 mm average size in coarser bands, down to 0.020 mm average size in finer grained bands.

Magnetite occurs as a dense cloud of fine or coarser particles arranged in thin laminae parallel to the bedding. The laminae may be so close as to form a single thick band of magnetite or may be as far as 0.25 mm apart. As a general rule, the further apart these laminae are the more microcrystalline quartz and the less calcite there is between them. Hence, closely spaced thick bands of iron ore contain abundant interlaminated calcite. The grain size of the magnetite is variable, thick bands containing the coarsest magnetite; thin bands in quartz

resemble trails of dust when seen under the microscope. On the average the magnetite is of slightly smaller size than the associated microcrystalline quartz.

Pyrite and minor pyrrhotite are found near the edges of the iron- and carbonate-rich bands, associated with a slightly coarser grained (recrystallized) quartz. They occur as irregular crystals of varying grain size, generally much larger than associated magnetite.

The association of pyrite in bands of magnetite and carbonate with a coarser grained quartz suggests that some of this coarser grained quartz has originated by metasomatic replacement of carbonate.

The variation in grain size of the microcrystalline quartz is most likely not primary, but is controlled by either recrystallization or secondary introduction.

Chlorite is associated with pyrite and coarser grained microcrystalline quartz.

The microscopic characters of other jaspilites, or of other specimens in the same formation, do not differ essentially from those above excepting:

- (1) where the jaspilite has suffered metasomatism in the ore shoots of the Hill 50 gold mine;
- (2) where the jaspilite has suffered metasomatism causing the development of actinolitic amphibole;
- (3) where the jaspilite has suffered metamorphism adjacent to the granite;
- (4) where the jaspilite outcrops at the surface, extending to an unknown depth, possibly hundreds of feet. Silicification of the carbonate in the jaspilite yields a banded microcrystalline quartz-iron ore rock.

Metasomatic changes in ore shoots.—39576 (11610E, 12905N, 820' level) is ore known at the mine as massive pyrrhotite. It is a heavy, metallic-lusted, bronze-yellow rock with a faint relict banding. Specific gravity = 3.86.

In thin section the rock appears massive and is composed dominantly of pyrrhotite and minor pyrite (45%), quartz (30%), and carbonate (25%). Extensive recrystallization has taken place in this rock, quartz occurring in all sizes from that of a normal jaspilite to 0.2 mm across. Calcite and pyrrhotite also occur in larger grains, averaging about 0.1 mm across.

It is concluded that metasomatic replacement of magnetite by pyrrhotite and minor pyrite has taken place. Most of the magnetite and carbonate was concentrated into bands before ore formation. The process of metasomatism has attacked these bands. Magnetite was replaced by sulphides and the carbonate recrystallized. Depending on the intensity of the metasomatism, the associated microcrystalline quartz was either poorly recrystallized for a short distance on either side of these iron- and carbonate-rich bands, or experienced all stages of recrystallization.

A. B. Edwards (1955, p. 35) reported: "The opaque minerals observed in the ore are magnetite and a trace of ilmenite, which are com-

ponents of the jaspilite rock forming the "host" rock of the mineralization and were not introduced by the mineralization, and pyrite, pyrrhotite, chalcopyrite, (?) galena and gold. The gangue introduced by the mineralization comprises quartz and a carbonate mineral." He concludes the "although the gold shows a distinct preference for association with quartz it is genetically related to the sulphides. This is apparent from the occurrence of occasional "veinlets" of gold, about 0.50 mm \times 0.005 mm, forming parts of pyrrhotite veinlets.

It is apparent also from the consistent association of the gold with areas in which sulphides are present, and its almost complete absence from areas lacking sulphides."

Surface silicification of jaspilites.—The evidence of surface silicification is:

(a) At depth, the jaspilites contain abundant carbonate, while at the surface they contain only traces of carbonate.

(b) At depth, the Perseverance Jaspilite and the (?) Jupiter Jaspilite contain primary nodules of calcite which are overlain directly by a band of calcite (approximately $\frac{1}{4}$ " to $\frac{1}{2}$ " thick). Whereas, at the surface these nodules are represented mainly by cavities in several cases, as in specimen 39514, they are composed of coarser microcrystalline quartz. Overlying these nodules at the surface is a band of microcrystalline quartz.

The depth to which the silicification extends is not known. Jaspilite on the 313' level appears to be highly siliceous in hand specimen while jaspilite from the 613' level downwards contains a high percentage of carbonate. In particular, one specimen is composed almost entirely of bedded carbonate and magnetite crossed by a vein of coarser microcrystalline quartz. The Hill 50 Jaspilite on the 1304' level appears to have a higher percentage of carbonate than at higher levels.

Within the quartz of the nodules of the Jupiter Jaspilite there are particularly numerous and often large inclusions of carbonate. The microcrystalline quartz in the body of the rock contains inclusions of carbonate of a much smaller size. These are harder to detect and their abundance is difficult to estimate.

Every thin section of jaspilite examined from the area, even underground on the 820' and 1060' levels, contained inclusions of carbonate of varying, generally minute size, in microcrystalline quartz. If these indicate silica replacement of carbonate, then a very large portion of each jaspilite must once have been composed of carbonate.

Surface silicification of jaspilites may be taken as proven. The silica in these jaspilites below the zone of surface silicification may have originated by metasomatic replacement of strata previously richer in carbonate. However, no valid criteria have been found to prove this hypothesis.

Environment of Deposition of the Boogardie Group

The great thicknesses of sediments, isoclinal folding and granite intrusion as in the Mount Magnet Greenstone belt are typical of ortho-

geosynclinal sequences. The lithologies in the Boogardie Group (flow lavas, bedded chemical and pelitic sediments and pure chemical sediments (jaspilites)) are characteristic of the eugeosynclinal suite of Kay (1951). Furthermore, tectonic instability is implied by the marked convergence of formations and members, by a buried hill structure and by slumping.

The provenance of the detritus is probably from within the eugeosyncline itself, rather than from without. That is, the clastic material (and some of the chemical) is primarily volcanic ejectamenta which has passed through the modifying influences of the normal processes of clastic and chemical sedimentation before deposition. No orthoquartzite, greywacke or arkose is intercalated in the section and the sequence cannot be ideally equated with the tectonic cycle of Krynine (1943, Fig. 1, p. 3).

The presence of small-scale cross lamination, ripple marking and scour-and-fill structures in the Boogardie Group is indicative of shallow-water depositional environments.

Structure

The eugeosyncline has been recognized as a wide, probably elongate, subsiding belt in which volcanic activity is dominant. Flow lavas and volcanic sediments form part of the geosynclinal filling. When they accumulated more rapidly than subsidence could accommodate them, volcanic islands were formed, contributed pelitic material to the geosyncline and then sank below sea-level, once subsidence overcame accumulation. As a consequence of sloping sea floors, members and formations were thickened or thinned and slumping of unlithified material occurred. Characteristically, the sediments of an eugeosyncline next become buried and suffer load metamorphism, isoclinal folding, faulting, intrusion by granite and metamorphism. The structures within the Boogardie Group described below are such that they could logically be explained by the above type of environment.

Primary Structures within the Boogardie Group

The following primary structures have been recognized within the Boogardie Group: buried valley structure; buried hill structure; calcareous nodules; ripple marking and associated scour and fill structure; cross lamination; thickening and thinning of units; slump structures and brecciation.

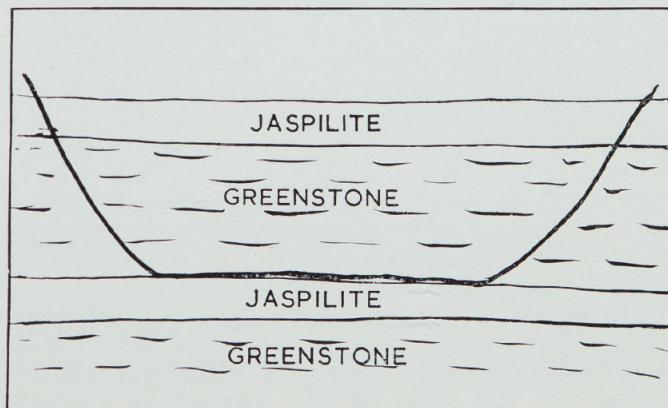


Fig. 5.—Initial stages in the development of a buried-valley structure showing the cutting of a channel.

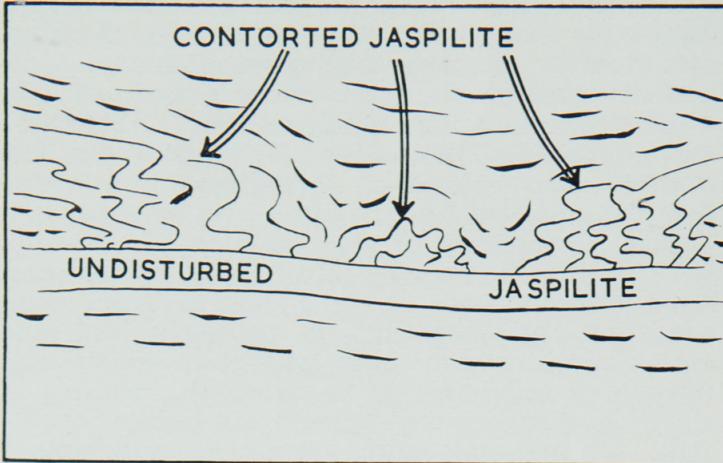


Fig. 6.—Final stage in the development of a buried-valley structure showing diagrammatically the way in which the upper jaspilite has slumped down onto the lower jaspilite, followed by burial.

Buried valley structure.—This structure is developed at 10880E, 14420N. Figs. 5 and 6 illustrate diagrammatically how the structure shown at this locality is thought to have developed. Initially, it is believed the two jaspilite members were conformably interbedded with greenstone (Fig. 5) and that subsequently a valley structure was developed by either slumping or scouring. Fig. 6 illustrates the manner in which the upper jaspilite member has slumped into the valley so formed, the whole being covered with later deposits of sediments.

Buried hill structure.—This structure has been mapped at 10120E, 14500N. Fig. 7A, B, C, D and Figure 8 illustrate diagrammatically how the structure at this locality is thought to have developed. Tectonism contemporaneous with sedimentation has been the cause of both thickness variations of the members and large-scale and small-scale slumping.

Calcareous nodules.—The Perseverance Jaspilite and the Jupiter Jaspilite contain small calcareous nodules. Fig. 9 is a thin section across a nodule in specimen 39585 from the Perseverance Jaspilite (1060' level of the Hill 50 gold mine). Laminae of chert, carbonate and magnetite underlying the nodule have been squeezed out in a compression fold. Overlying the nodule there is a band of carbonate and iron ore in which cross-bedding and gravity differentiation of the minerals may be seen. Above this latter band are laminae of chert, carbonate and magnetite. The author believes that the nodule grew by a process of chemical accretion upon the depositional interface and that the weight of the nodule was sufficient to depress the laminae beneath it, adjustment being a compression fold in a lateral direction. The growth of the nodule was halted by the coagulation in the overlying waters of carbonate and iron ore. These were precipitated and the iron ore (by reason of its higher specific gravity) became separated from the carbonate. On reaching the depositional interface the first of the carbonate and magnetite to arrive was cross-bedded off the side of the protuding nodules (supratenuously). Subsequent precipitation smoothed the new depositional interface.

Ripple marking and associated scour and fill structure.—Ripple marking has been found in unit 7 of the Mars Greenstone (specimen 39546) (see Fig. 4). The cross lamination of the ripple ridges and the collection of magnetite grains in the deepest part of the trough serves to distinguish these structures from the fill structures in the ripple valleys (Shrock 1948, p. 104). The fill structures possess cross-lamination in which the foreset laminae are asymptotic with one slope and are sharply truncated on the other slope. Magnetite and biotite are distributed at the base of the foreset laminae.

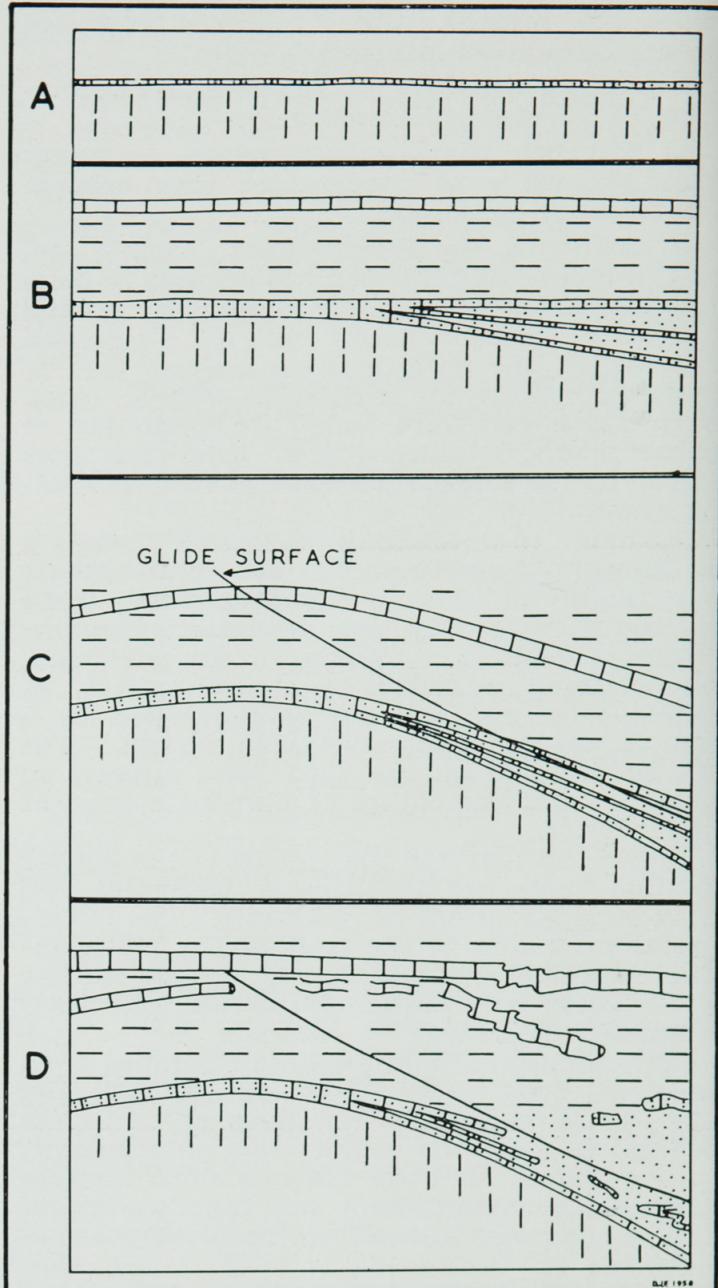


Fig. 7.—Initial stages in development of buried hill structure at 10120E, 14500N.

- Deposition of the Poverty Flat Formation and portion of the Jupiter Jaspilite.
- Monoclinal warping during deposition of the remainder of the Jupiter Jaspilite and subsequent deposition of the first two units of the Mount Magnet Greenstone.
- Repetition of the warping to produce a hill structure. Slumping commenced due to steepening of depositional dip.
- Normal sedimentation established over the slumped sediments, unit 3 of the Mount Magnet Greenstone was laid down on a slightly sloping sea floor and subsequently slumped.

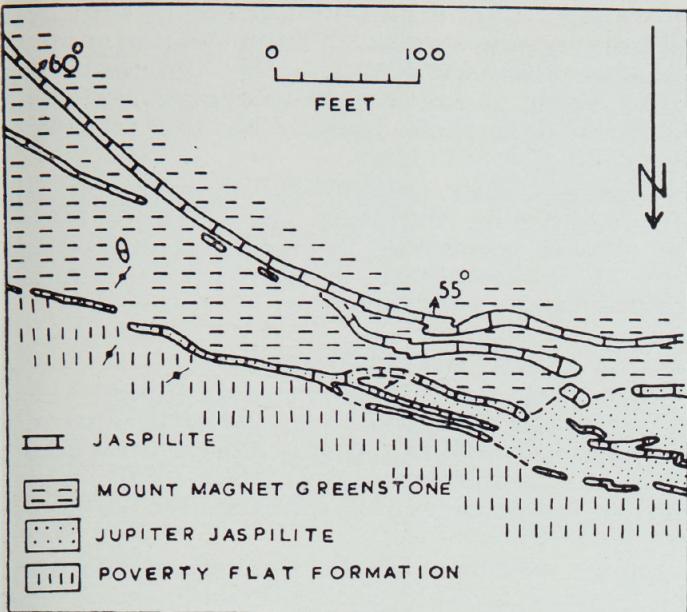


Fig. 8.—The buried hill structure as mapped after regional tectonic deformation has been superimposed on the initial structure.

Cross lamination.—Small scale cross lamination is developed within unit 7 of the Mars Greenstone.

Thickening and thinning of units.—The rapid thickening and thinning of formations and members has been demonstrated earlier in the section dealing with the stratigraphy of the Boogardie Group.

Slump structures and brecciation.—The differentiation of slump structures and tectonic structures depends upon criteria related to the different modes of origin of the two features. The following criteria have been used where possible to determine the origin of contortions in the jaspilites:—

(1) A highly puckered contortion of small amplitude, contained within relatively undisturbed beds, suggests gravity slumping.

(2) Broad folds of large amplitude, repeated in the underlying and overlying strata indicate tectonic folding.

(3) A distinct or probable lineation running parallel to the axis of a fold or series of folds is evidence for tectonic drag folding, except in the limiting case where the impressed lineation coincides with the axes of true slump folds.

(4) Strata are considered to be slumped where the folded beds are overlain by a local unconformity.

(5) Slump folds are overturned towards the depression whereas tectonic folds are overturned towards the anticlines.

Many of the incompetent folds in the Boogardie Group are indeterminate in origin. Slumping requires a suitable unlithified state of the sediment and either an initial slope of the depositional interface or an external source of energy such as could be provided by outpourings of basic lava. These conditions are thought to have existed during the deposition of many of the jaspilites.

Slumping has been used above to indicate top and bottom. Another use is to be found in the correlation of jaspilite members. Slumping being a primary feature could be typical of certain units. Attention to slump features during mapping might enable the correlation of sporadic outcrops and of strata on each side of fault blocks.

Tectonic Structures

The tectonic structures are folds, faults and joints which have developed after deposition and compaction of the sediments.

Folds.—Two types of folds have been recognized, namely regional folds and drag-folds.

Fig. 1 illustrates the regional structure. The Boogardie Group and the Lennonville Beds are folded into a tight, southerly plunging, inclined syncline which has characteristics as follows:—

- (1) The axial plane trends 207° (S.S.W.).
- (2) The west limb of the syncline strikes approximately 225° (S.W.) and dips approximately 60° E.
- (3) The east limb of the syncline strikes approximately 150° (S.E.) and dips between 75° E. and 75° W.
- (4) The lineation in hornblende schists adjacent to the granite on the western limb plunges 40° - 65° S. in the direction 155° to 190° (S.E.-S.).

The folding has been interpreted as the result of granite intrusion (see General Stratigraphy).

Drag-folds related to larger fold structures are recognizable where they are not disharmonic. The typical example is on the 313' level of the Hill 50 gold mine at (11623E, 12180N). At this locality the junction between the Saturn Formation and the underlying Havelock Greenstone is drag-folded. The north-plunging drag-fold is related to the main north-plunging anticlinal drag-fold of the mine at that level. The 'Main Oreshoot' of the Hill 50 gold mine is structurally controlled by a drag-fold (probably related to the 'Boogardie Break' system) and there are numerous disharmonic folds which are unreliable for structural interpretation.

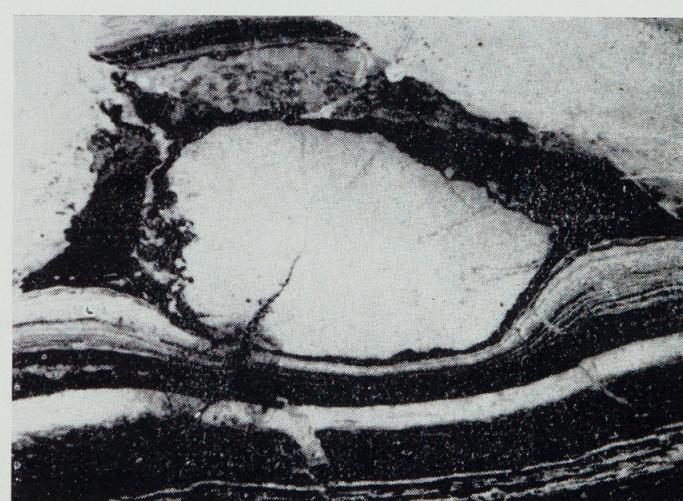


Fig. 9.—Thin section of a calcite nodule in the Perseverance Jaspilite. Ordinary light X2.

Drag of strata against faults is widespread in the Boogardie District. The direction of the drag indicates the direction of the movement. The large east-west fault which cuts the north-west corner of the area shows a fine example of drag adjacent to faults.

Faults.—The Boogardie Group is traversed by many faults and the most complex faulting is found in the vicinity of the Hill 50 gold mine. The faulting is believed to have developed during a late stage of regional folding prior to the consolidation of granite because the fault surfaces are not folded and the granite-greenstone contact appears unfaulted.

Three major faults trend sub-parallel to the major synclinal axis, the Hill 50 Fault being typical with a throw of approximately 600 feet. Two of these faults are sinistral, the other dextral.

Two later shears cut this system of faults. One cuts the north-west corner of the area in an east-west direction, and the other is the Main Fault of the Hill 50 gold mine which runs in a north-south direction. They are believed to be the result of thrusting on each flank of the syncline downwards towards its nose.

The 'Boogardie Breaks' are faults of minor throw which trend sub-parallel to the Hill 50 Fault (N.E.). The 'Breaks' are exposed on 414' level of the Hill 50 gold mine where a number of them form the channels of porphyry intrusion. Their movement is dominantly dextral both on the 414' level and to the south of this level. North of the 414' level their movements are both dextral and sinistral. These faults are not folded against the Main Fault and they do not appear to cross or displace the Main Fault. For this reason they are probably complementary faults. Movement along the Main Fault may have arched the sediments on either side and the relief of this arching was marked by a tensional shattering and porphyry intrusion along the tensional faults, the 'Boogardie Breaks', and along tensional sections of the Main Fault.

The porphyries are cut by a system of flat-dipping reverse faults, striking parallel to and antithetic towards the Main Fault.

On the 313' level of the Perseverance workings the 'Boogardie Breaks' are cut by a flat-dipping fault, parallel in strike to the strike of the flat-dipping faults above but dipping in the opposite

direction. This strike fault is cut in turn by a steeply dipping transverse fault, striking approximately 290° (W.N.W.). On the 820' and 1060' levels of the Hill 50 gold mine there is a dolerite-filled fault parallel to the transverse fault on the 313' level.

Joints.—Joints are well-developed in the Hill 50 Jaspilite on the Mars lease, G.M.L. 1438M; in several porphyries underground and within the Mars Greenstone in the 313' level of the Perseverance workings.

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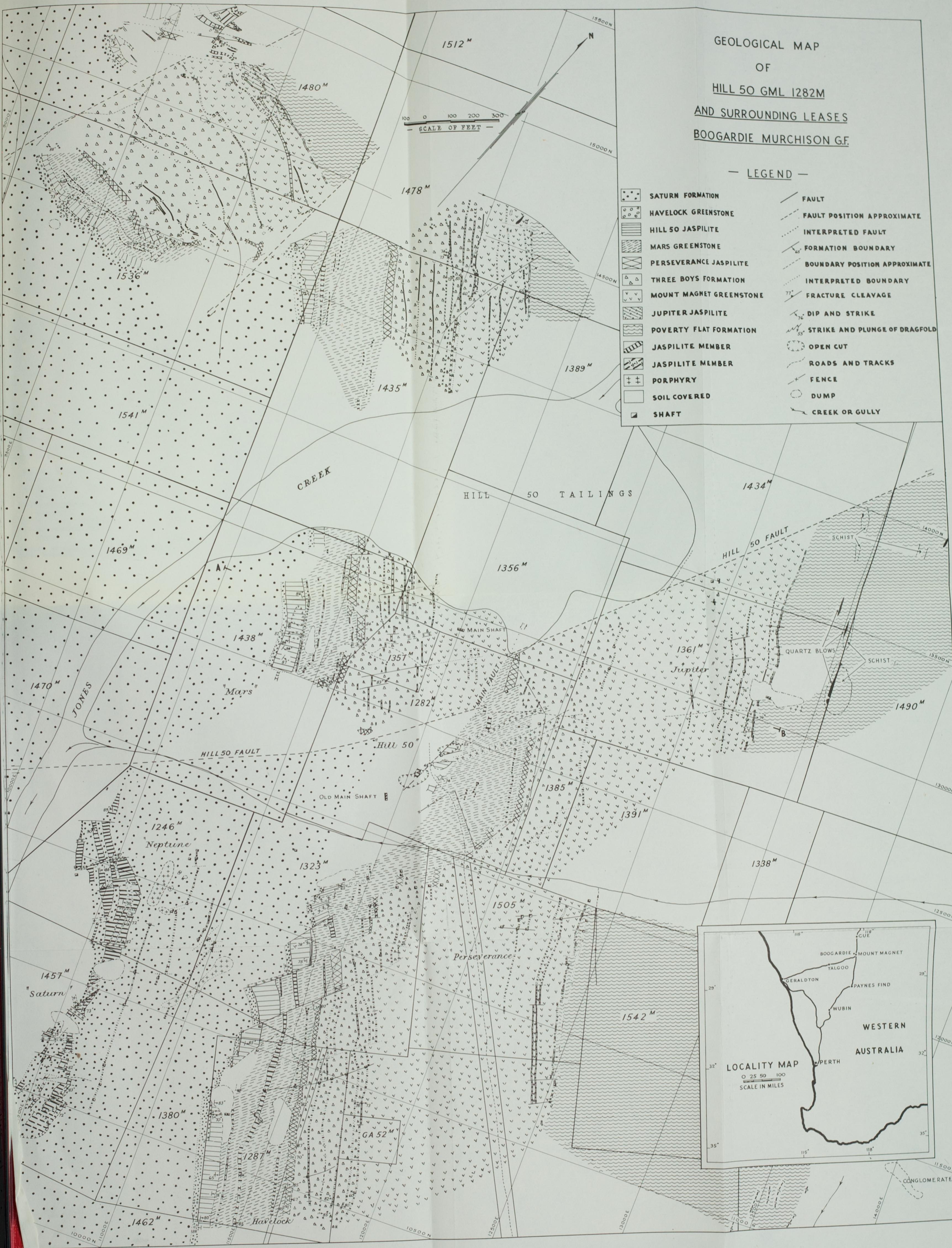
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GEOLOGICAL MAP
OF
HILL 50 GML 1282M
AND SURROUNDING LEASES
BOOGARDIE MURCHISON G.F.

— LEGEND —

| | |
|-------------------------|-------------------------------|
| SATURN FORMATION | FAULT |
| HAVELock GREENSTONE | FAULT POSITION APPROXIMATE |
| HILL 50 JASPILITE | INTERPRETED FAULT |
| MARS GREENSTONE | FORMATION BOUNDARY |
| PERSEVERANCE JASPILITE | BOUNDARY POSITION APPROXIMATE |
| THREE BOYS FORMATION | INTERPRETED BOUNDARY |
| MOUNT MAGNET GREENSTONE | DIP AND STRIKE |
| JUPITER JASPILITE | STRIKE AND PLUNGE OF DRAGFOLD |
| POVERTY FLAT FORMATION | OPEN CUT |
| JASPILITE MEMBER | ROADS AND TRACKS |
| JASPILITE MEMBER | FENCE |
| PORPHYRY | DUMP |
| SOIL COVERED | CREEK OR GULLY |
| SHAFT | |



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Part 4

12.—A Contribution to the Petrology of the Yandanooka Group

By J. E. Glover*

Manuscript received—21st June, 1960

The Yandanooka Group is a thick (approximately 30,000 ft.) sedimentary sequence in the Yandanooka area, west of the Darling Fault Zone in Western Australia. Formations in the group, from the base upward, are: Arrowsmith Sandstone, Arrino Siltstone, Beaconsfield Conglomerate, Enokurra Sandstone and Mt. Scratch Siltstone. They represent deposits ranging from probable continental facies, through littoral to somewhat deeper water facies. Lithologic types include conglomerates, feldspathic quartz sandstones, arkoses, lithic sandstones, siltstones and shales. All formations except the Enokurra Sandstone contain a notable proportion of volcanic fragments. Much of the volcanic material was clearly derived from erosion of extrusive rocks, but some of the volcanic material in the Mt. Scratch Siltstone appears to be tuffaceous, and probably represents volcanism that occurred during sedimentation. Conglomerates in the group contain numerous spilitic pebbles and cobbles.

The high proportion of labile grains (such as feldspar, and granitic and volcanic fragments) indicates the absence of effective chemical weathering. This was probably a result of rapid erosion and transport from a hinterland of strong relief. The sediments appear to have been laid down in a basin that subsided considerably during deposition.

Introduction

The Yandanooka Group is a thick sequence of unfossiliferous sedimentary rocks bounded by Precambrian rocks of the north-north-westerly trending Mullingarra Inlier to the west, and the Darling Fault Zone to the east (see Fig. 1). Formations in the Yandanooka Group have an aggregate thickness of about 30,000 feet, and have been formally defined by Playford and Willmott in McWhae, Playford, Lindner, Glenister and Balme (1958). Other reference to these rocks has been made by Campbell (1910), Woolnough and Somerville (1924), Baker (1951), Johnson, de la Hunty, and Gleeson (1954) and Glover (1958a). The age of the rocks is doubtful, and is considered by McWhae *et al.* to be late Precambrian or early Palaeozoic.

The sequence according to McWhae *et al.* may be summarized as follows:

| | ft. |
|-----------------------------|---------------|
| 5—Mt. Scratch Siltstone | 25,000-30,000 |
| 4—Enokurra Sandstone | 680 |
| 3—Beaconsfield Conglomerate | 130 |
| 2—Arrino Siltstone | 1,670 |
| 1—Arrowsmith Sandstone | 1,100 |

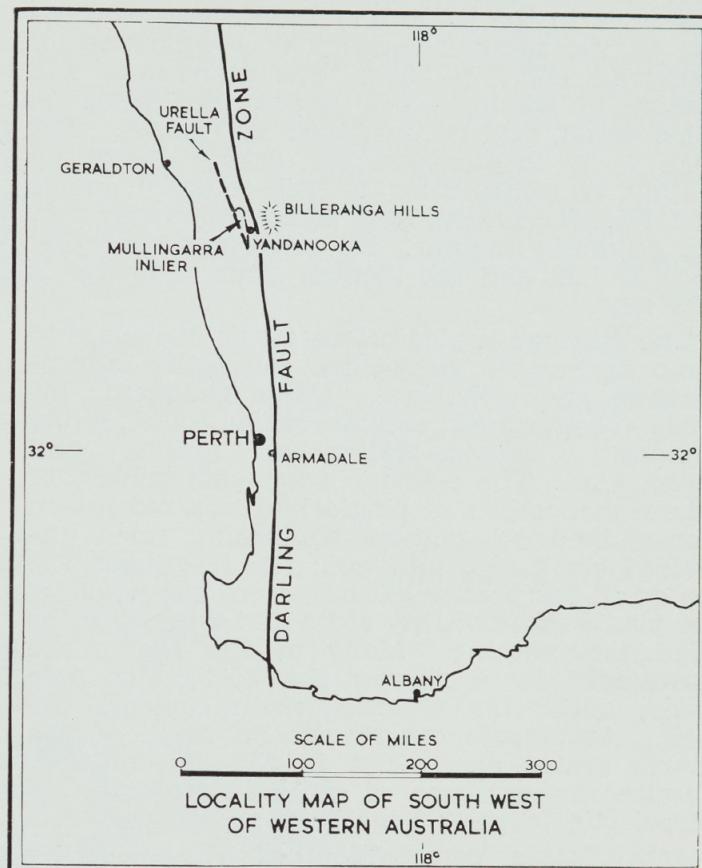


Fig. 1.—Locality map showing the Yandanooka area.

With the exception of Mt. Scratch Siltstone and Enokurra Sandstone, thicknesses are quoted from type sections of formations. Incomplete thicknesses are represented at the type sections of Mt. Scratch Siltstone and Enokurra Sandstone.

In the present study, 36 specimens from the Yandanooka Group were examined under the petrologic microscope and three specimens previously described by Simpson and Glauert (in Campbell 1910) were re-examined. A description of the Beaconsfield Conglomerate, based on the study of 14 thin sections, has already been published (Glover 1958a), but results are incorporated here. Specimens whose numbers are prefixed by the letters Pf were made available by West Australian Petroleum Pty., Ltd.: other specimens are those of the Geology Department of the University of Western Australia.

No detailed maps showing the distribution of the Yandanooka Group have so far been published, and further work may result in finer

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subdivision of this thick sequence and in the collection of rock types not described here. Moreover, the group has not been drilled (apart from shallow water bores) and no subsurface samples are available. Nevertheless, the 53 specimens studied are probably sufficiently representative to justify a preliminary discussion of the petrology.

Arrowsmith Sandstone Petrography

The Arrowsmith Sandstone is a uniform sequence of well-bedded, medium- to coarse-grained sandstone that contains abundant feldspar and lithic fragments. All specimens examined in the laboratory are arkoses, according to the tabular sandstone classification of Pettijohn (1957, p. 291). The mineralogy and texture of specimen Pf2 is described below in some detail, and is illustrated in Fig. 3A. The rock is a medium-grained arkose made up mainly of sub-angular to well-rounded quartz and feldspar grains, and lithic fragments that are generally angular. Its coefficient of sorting (S_o) is 1.39 and the median grain diameter is 0.33 mm.

The feldspar is plagioclase (sodic oligoclase to sodic andesine), microcline, microcline microperthite and orthoclase. Lithic fragments include volcanic rock, sericite-quartz schist, many composite quartz-feldspathic grains, and myrmekite. The volcanic fragments consist of micro-phenocrysts of plagioclase in a red-brown iron-stained groundmass containing some unaltered black iron minerals; the fragments are too small for precise classification, but much of the plagioclase is fairly sodic and appears to be oligoclase-andesine. Many of the grains are surrounded by a narrow rim of fibrous, pale green, authigenic chlorite which cements the rock. Authigenic outgrowths on some of the quartz grains also assist in the cementation. Despite the presence of volcanic material, no vitroclastic textures have been recognized.

Approximate composition of the rock by volume is:

| | Per cent |
|------------------------|----------|
| Quartz | 40 |
| Feldspar | 27 |
| Volcanic fragments | 13 |
| Other lithic fragments | 13 |
| Cement | 6 |
| Other minerals | 1 |

Heavy minerals were separated in bromoform from the fraction with grain diameters between 0.66 mm and 0.124 mm, and compose about 15 per cent. of that fraction. Volcanic fragments (generally angular) and rounded black opaque grains (ilmenite with a little magnetite) are abundant. Some of the volcanic fragments are attracted by ordinary bar magnet, and at least part of their contained iron minerals is therefore magnetite. Pale pink, slightly magnetic, angular, strongly etched garnet is common, and much of it is partly altered, apparently to a mixture of feldspar and white mica. Clear garnet grains have a refractive index close to 1.810 and they are probably almandine. Other common heavy minerals are sphene and zircon.

The sphene is cloudy and angular, and there are three varieties of zircon: colourless to pale brown, very well-rounded grains; colourless to pale brown, zoned, well-rounded grains; and rare lilac euhedra. Rare heavy minerals include rounded apatite, brown and black, rounded and angular tourmaline, and rounded rutile.

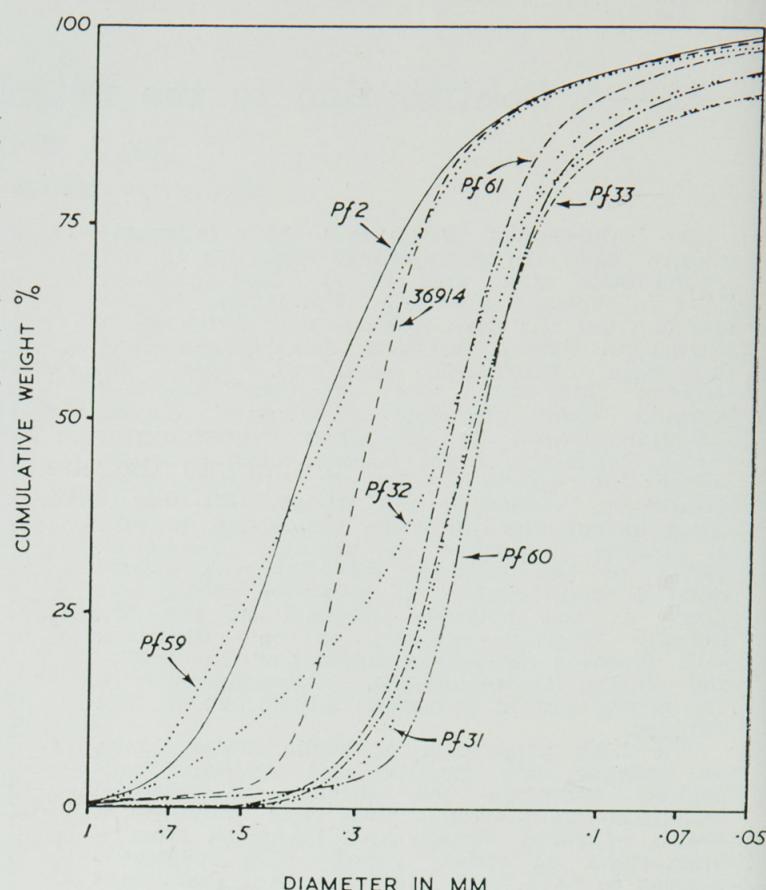


Fig. 2.—Cumulative weight per cent curves of 8 specimens of Arrowsmith Sandstone. The abscissae are on a logarithmic scale. Note the high degree of sorting of most specimens.

Eight specimens of Arrowsmith Sandstone (36914, Pf 2, Pf 31, Pf 32, Pf 33, Pf 59, Pf 60, Pf 61) were disaggregated by maceration in water, and after mechanical analysis, cumulative weight per cent curves were constructed (Fig. 2). The curves do not precisely represent the original sorting of the rock, which has changed after deposition by secondary enlargement of some quartz grains and transformation of cement to fibrous chlorite. Nevertheless, the curves probably indicate fairly closely the original sorting. The coefficient of sorting ranges between 1.18 and 1.50 indicating a well-sorted sediment (Trask 1932) and falls within the range of sorting of most near-shore marine sediments of sand grade, according to Hough (1942).

The roundness of the quartz grains was compared with the standards set forth by Krumbein (1941). No precise grain counts were attempted, as an unknown number of grains have an induced angularity due to authigenic growth, but some significant features are evident. Quartz grains smaller than 0.124 mm in diameter are practically all angular (.2 to .3), some grains in the 0.124-0.246 mm range are slightly rounded (.4 to .5), many grains in the

0.246-0.495 mm range are moderately well-rounded (.5 to .6) and most coarser grains are well-rounded (.6 to .8). It would appear from the investigations of Kuenen (1959) that the grains must have been modelled by either wind or surf, and the earlier work of Twenhofel (1945) suggests that wind traction may have been a factor in rounding the grains of less than 0.495 mm diameter. The grains seem to have been rounded in one cycle, for no earlier formation capable of yielding rounded grains has so far been recognized in the area.

Environment of Deposition

The parameters discussed above are consistent with a near-shore, marine environment. The abundant labile grains, such as feldspar and volcanic fragments, indicate the absence of effective chemical weathering. This may have resulted from rigorous climatic conditions, but other factors discussed at the end of the paper suggest that climate was not the main influence. It is more likely that dominantly mechanical disintegration, and rapid transport to the site of deposition, prevented soil formation, with its attendant chemical transformation of unstable grains. The Arrowsmith Sandstone was derived from a granitic, meta-sedimentary and volcanic terrain that was therefore probably fairly rugged, and it appears to have been deposited near the strand line of a subsiding basin.

Arrino Siltstone

Petrography

The Arrino Siltstone is a uniform sequence of poorly bedded, dark, reddish brown, micaceous siltstone that rests conformably on the Arrowsmith Sandstone. Four specimens (Pf 3, Pf 4, 36915, 36916) were examined microscopically. The rocks are sandy siltstones, with quartz content ranging from 37-73 per cent and all contain numerous lithic fragments which are generally concentrated in the coarser fractions. The content of volcanic fragments ranges from 7-15 per cent and that of other lithic fragments from 10-43 per cent. The volcanic fragments consist of micro-phenocrysts of plagioclase in a red-brown, iron-stained matrix that also contains abundant black magnetite; the other fragments include garnet granulite, muscovite-biotite-quartz schist, chlorite-quartz schist, (?) chert, epidote-quartz rock, and other composite grains commonly containing quartz, carbonate and chlorite. Feldspar (plagioclase and microcline) comprises up to 5 per cent of the siltstone. Both sand and silt grains are generally angular, and are commonly cemented by pale green, locally fibrous, chloritic cement that constitutes from 3-8 per cent of the rock. In places, the cement is stained red-brown. Specimen 36916 is illustrated in Fig. 3B.

None of the rocks examined contains recognizable vitreous texture, and there is no evidence that they are tuffaceous.

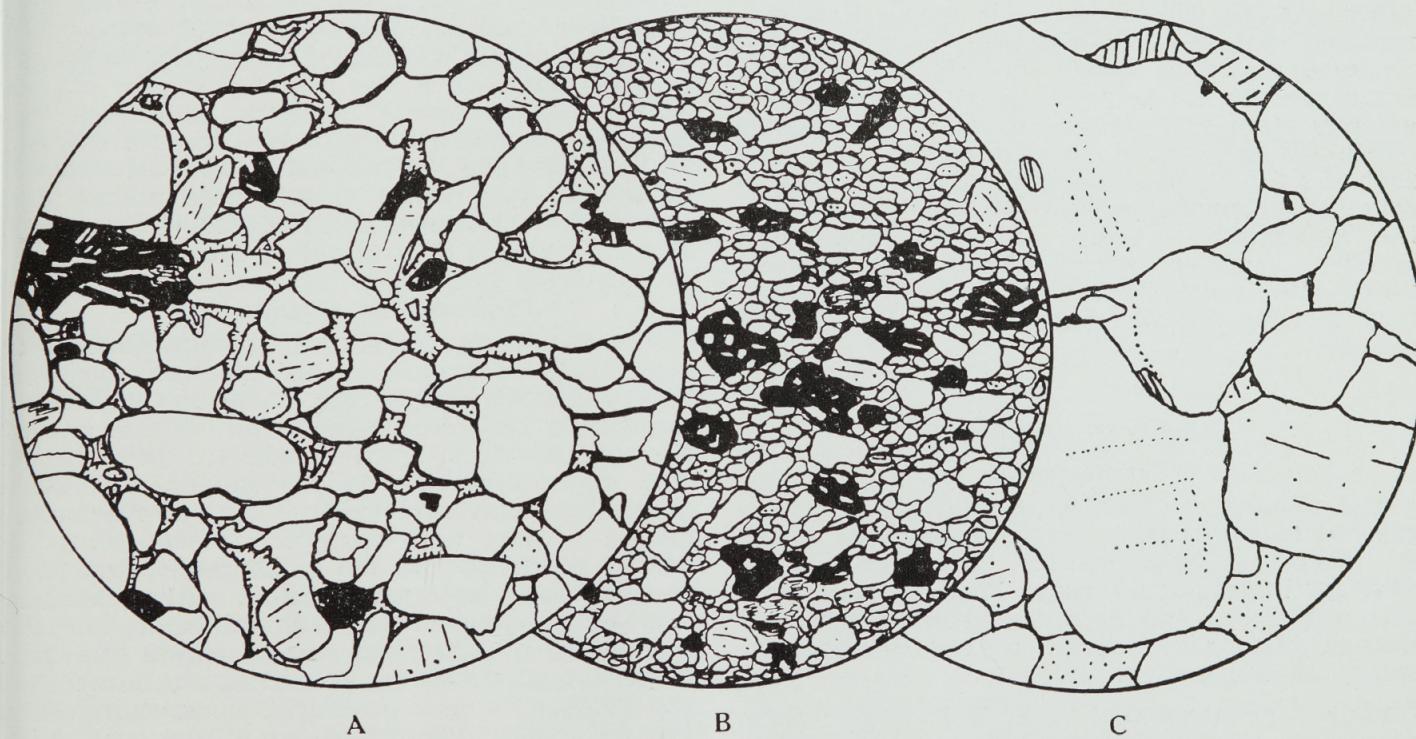


Fig. 3.

- A.—Arrowsmith Sandstone (specimen Pf2). Clear grains are quartz and stippled grains with cleavage are feldspar. Lithic fragments are volcanic rock (dark) and grains of interlocking quartz. One quartz grain (lower left centre) shows authigenic enlargement, and there are more angular grains than is usual in this field. Cement is fibrous chlorite. Diameter of field 2.4 mm.
- B.—Arrino Siltstone (specimen 36916). Clear grains are quartz, stippled grains with cleavage are feldspar and dark grains are volcanic. Fine grains are commonly difficult to identify, but most are quartz. Cement is sparse and forms an iron-stained rim to most grains. Diameter of field 2.4 mm.
- C.—Enokurra Sandstone (specimen 38725). Clear grains are quartz, stippled grains with cleavage are feldspar and lined grains are muscovite. Cementation is by enlargement of quartz grains and by clay-sized and sericitic matrix (closely stippled). Diameter of field 2.4 mm.

Environment of Deposition

The Arrino Siltstone was apparently derived from a similar provenance to that of the Arrowsmith Sandstone, but seems to represent a deeper water facies. The same factors that led to preservation of unstable grains in the Arrowsmith Sandstone were presumably operative during deposition of the Arrino Siltstone.

Beaconsfield Conglomerate

The Beaconsfield Conglomerate, which crops out toward the western side of the basin, conformably overlies the Arrino Siltstone, and is made up almost entirely of rounded pebbles and cobbles of volcanic rock. A few pebbles of granitic rock, quartzite and sandstone are also present. The petrology of the Beaconsfield Conglomerate has been described previously (Glover 1958a).

The coarseness of the Beaconsfield Conglomerate contrasts with the fineness of the underlying Arrino Siltstone, and its relative homogeneity (mainly volcanic detritus) contrasts with the mixed volcanic, granitic and meta-sedimentary detritus making up the Arrino Siltstone.

Baker (1951, p. 20) thought that the conglomerate was due to increased outpourings of lava combined with penecontemporaneous uplift to the west, and that the boulders were deposited under relatively shallow water conditions. He disagreed with Johnson *et al.* (1954, p. 43) who believed it to be a water-rounded volcanic agglomerate. The present writer agrees with Baker that the Beaconsfield Conglomerate has probably been derived almost entirely from the volcanic cover of an uplifted block. It may have been deposited near the foot of a fault scarp in a shallow marine or even continental environment. However, in view of the petrographic range of the pebbles and boulders (spilites, micro-diorites and volcanic rocks transitional between them), their origin may be less straight-forward than it at first appears.

Enokurra Sandstone

Petrography

The Enokurra Sandstone consists of fine-grained to very coarse-grained sandstone which is locally conglomeratic. It shows well-developed large-scale cross bedding and rests with erosional unconformity on either the Beaconsfield Conglomerate or the Arrino Siltstone (McWhae *et al.* 1958).

Four specimens (Pf1, Pf5, Pf6, 38725) were examined microscopically. The rocks range from feldspathic sandstone to arkose (10-43 per cent feldspar) and three of them contain significant amounts (5-15 per cent) of quartz-feldspathic lithic fragments. Cement constitutes less than 10 per cent, and the sorting of the grains, which are generally angular, ranges from moderately good to poor.

Specimen 38725 (Fig. 3C), a coarse-grained arkose, with conglomeratic bands, is described

below. Its approximate composition by volume is:

| | Per cent |
|------------------------------------|----------|
| Quartz | 67 |
| Feldspar | 15 |
| Lithic fragments | 14 |
| Muscovite, garnet, opaque minerals | 2 |
| Clay-sized material, iron oxide | 2 |

The feldspar consists of microcline and of oligoclase replaced partly along cleavages by muscovite. Both varieties of feldspar are somewhat kaolinized, but the oligoclase is generally more strongly altered. Lithic fragments are mainly interlocking quartz with undulose extinction, and some contain microcline, microcline microperthite, muscovite and green-brown biotite. Much of the quartz in these composite grains is traversed by lines of minute inclusions, and commonly contains minute needles of unknown composition, and cracks filled with limonite. The composition of the feldspar, and the mineralogy and texture of the lithic fragments point strongly to their derivation from rocks like the quartz-oligoclase-microcline-biotite gneiss of the Mullingarra Inlier described by Baker (1951, p. 33). Other fragments include myrmekite and muscovitic quartzite. Cementation of the rock is effected partly by muscovite, clay-sized material and limonite, and partly by authigenic quartz outgrowth.

Approximately 10 grams of specimen 38725 were crushed, and 0.3 grams of heavy minerals were present in the grade containing grains with diameters ranging from 0.61-0.125 mm. The heavy minerals consist of ilmenite, generally angular but with a few rounded grains (62 per cent): garnet, weakly magnetic, pale pink and strongly etched, with refractive indices ranging from 1.810-1.815 (31 per cent): apatite, strongly etched (6 per cent): zircon, pale mauve and euhedral, dark brown and rounded (1 per cent): and rare grains of tourmaline and sphene.

Environment of Deposition

The Enokurra Sandstone is separated from underlying sediments by an unconformity, and differs lithologically from them in containing practically no volcanic material. It was clearly derived therefore, from a different provenance. The abundance of feldspar in the formation shows that chemical weathering was ineffective during erosion and deposition. The generally coarse grain size of the sandstones, and their coarse cross bedding, indicate either shallow marine or continental sedimentation, and the angularity of the sand grains shows the lack of prolonged working. It is likely therefore that the basin, although shallow, was subsiding. The few observations made so far of the cross bedding indicate derivation from the north-west or north-north-west.

Mt. Scratch Siltstone

Petrography

The dominant lithology of this thick formation is siltstone, but abundant shale and some fine- to coarse-grained sandstones occur locally within it, and some conglomeratic lenses were

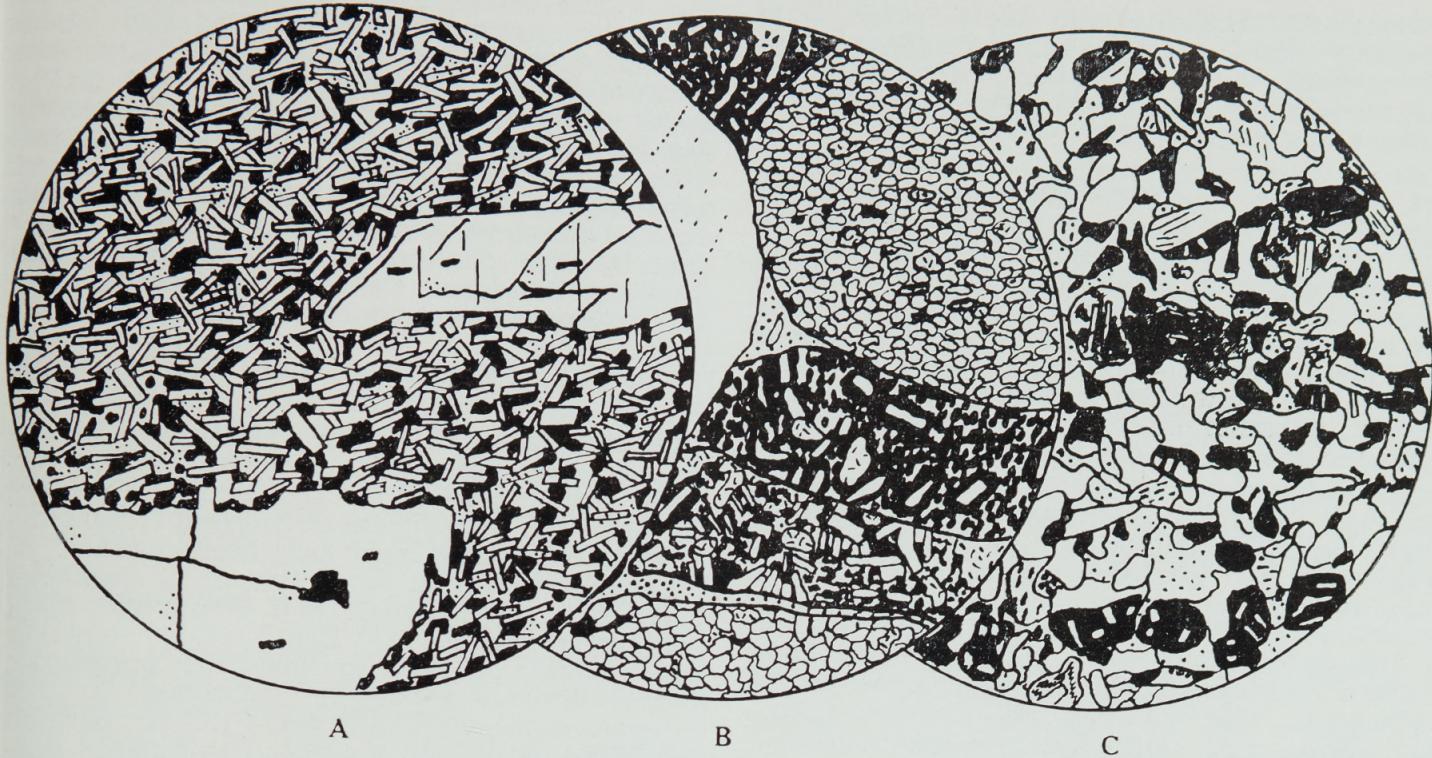


Fig. 4.

A.—Pebble of spilitic lava from conglomerate in Mt. Scratch Siltstone (specimen 38705). Partly altered phenocrysts of albite, traversed by ironstained cracks, are set in a matrix of iron ore (black) and chloritized and epidotized sodic plagioclase. Diameter of field 8 mm.

B.—Very coarse-grained lithic sandstone from Mt. Scratch Siltstone (specimen 36921). Fragments include metamorphozed siltstone (top right and bottom), chert (top left) and chloritized and epidotized volcanic rock. The sparse cement (stippled) is a mixture of clay-sized material, quartz and epidote. Diameter of field 2.4 mm.

C.—Very fine-grained sandstone in Mt. Scratch Siltstone (specimen Pf7). Clear grains are quartz, dark grains are volcanic rock, stippled grains are chlorite, dashed grains are epidote. The rock may be partly tuffaceous. Diameter of field 2.4 mm.

encountered. Pebbles and cobbles in the conglomerate are generally well rounded and are red-brown from weathering: 14 of them were examined microscopically, and are classified as follows:

- Micro-porphyritic, chloritized volcanic rock (38705, 38705a, 38708, 38711).
- Sheared epidote-quartz rock (38704, 38710, 38710a).
- Sheared and partly mylonitized feldspathic sandstone (38709, 38711a).
- Granitic gneiss (38703, 38707).
- Feldspathic quartzite (38706).
- Chlorite schist (38708a).
- (?) Hornfels (38709a).

The four pebbles of volcanic rock listed above are of spilitic composition, and one of them (specimen 38705) is briefly described below. It contains plagioclase phenocrysts up to 3 mm long in a groundmass made up of plagioclase laths ranging from 0.3 mm to 0.6 mm in length, black iron ore (mainly magnetite) haematite, limonite and rare patches of quartz. Approximate composition of the rock by volume is:

| | Per cent |
|---------------------------|----------|
| Plagioclase (phenocrysts) | 10 |
| Plagioclase (groundmass) | 64 |
| Iron ore | 25 |
| Quartz | 1 |

Plagioclase phenocrysts are traversed by red, iron-stained cracks and are altered locally to chlorite, epidote and quartz. Plagioclase laths

in the groundmass are more extensively altered, and are generally cloudy. All the feldspar is highly sodic. Cleavage fragments of one phenocryst showed the following indices:

$$\begin{aligned} Ng \ (001) &= 1.541 \pm .001. \\ Ng \ (010) &= 1.536 \pm .001. \\ Np &= 1.531 \pm .001. \end{aligned}$$

Composition (Winchell and Winchell 1956) is therefore close to An_7 . Many grains have somewhat patchy extinction, and even where extinction is fairly uniform, measurements with the universal stage show certain optical anomalies.

It is common in sections $\perp a$ for readings of $X' \wedge 010$ to differ considerably in adjacent subindividuals of the same crystal. Thus one crystal showed $X' \wedge 010 = 12^\circ$, $X' \wedge 010 = 17^\circ$ in adjacent lamellae, indicating compositions respectively of An_6 and An_0 . These anomalies may be due to an unusual cooling history of the phenocrysts, but no more precise reason for them can be advanced at present.

A coarse-grained lithic sandstone (specimen 36921) from the formation is illustrated in Fig. 4B. It consists of well-sorted, rounded to sub-angular fragments mostly about 2 mm in diameter, cemented by a sparse fine aggregate of quartz, chlorite, epidote and clay-sized material. About 80 per cent of the grains are of volcanic rock but they are too altered for effective determination. None of the feldspar in them seems more calcic than

intermediate andesine and most seems considerably more sodic. Other fragments are fine-grained quartzite, chert, (?) hornfels, chlorite-quartz schist, chlorite-epidote-quartz schist and granitic rock.

Other specimens include siltstone (38712, Pf8, Pf9, Pf10) and very fine-grained sandstone (Pf7). Volcanic fragments make up part of the rocks (13-45 per cent) and other constituents are quartz, plagioclase, epidote, chlorite, muscovite, biotite and minor microcline. Grains are generally angular. Heavy minerals from Pf7 (apart from volcanic fragments) are sparse, and include subrounded to well-rounded apatite, cloudy epidote, colourless, angular, faintly magnetic garnet, biotite and rare pyroxene.

No undoubted vitroclastic texture has been observed in the fine-grained rocks described above, but a few pale brown, weakly anisotropic fragments that probably represent devitrified glass shards are present in them. Moreover, some volcanic fragments have unusual shapes, as though deposited when plastic. These fine-grained rocks are likely therefore to be partly tuffaceous. Unfortunately, fine-grained, water-laid, lithic tuffs and fine-grained sediments derived from erosion of a volcanic landmass are not easily distinguished, even if of fairly recent origin. In neither sediment are grains likely to be rounded, and proof of tuffaceous origin is to be sought in the presence of glass shards, pumiceous fragments and embayed crystal fragments as described by Pirsson (1915). The glass of submarine tuffs may alter rather quickly however (see for example Müller (1958) on Recent sediments in the Bay of Naples), and the features listed by Pirsson tend to become unrecognizable under the influence of compaction and diagenesis in older rocks such as those of the Yandanooka Group. It is clear, however, that much of the material is of normal, epiclastic origin, for it has been derived from granites and meta-sediments. It is also evident that volcanic fragments in the conglomerates and coarse-grained sandstones are epiclastic, for they are rounded, and are associated with rounded fragments of similar size which are not of volcanic origin.

Environment of Deposition

The Mt. Scratch Siltstone is a thick (25,000-30,000 ft.), generally fine-grained sequence derived from a terrain of volcanic, granitic and meta-sedimentary rocks. Volcanism was apparently active during sedimentation: some volcanic material was derived from erosion of the landmass, whereas some was probably blown directly from volcanoes to the basin of deposition and incorporated in the accumulating sediment. The fine-grained rocks probably represent a mixture of epiclastic and pyroclastic deposition.

The general fineness of the formation suggests deeper waters than those prevailing during deposition of the Arrowsmith Sandstone, Beaconsfield Conglomerate and Enokurra Sandstone. Ripple marks have been observed locally by Playford (pers. comm.), but without careful study their value as a criterion of shallow water deposition must be accepted cautiously. Cur-

rent ripple marks have now been observed on seamounts at depths of over 4,000 feet in recent oceanographical work (Dietz and Menard 1951, p. 2004; Heezen, Thorp and Ewing 1959, p. 59). Small scale cross bedding is a characteristic feature of the formation, but its significance with regard to depth of sedimentation is not understood. The great thickness of the Mt. Scratch Siltstone, and the fact that it is underlain by the shallow marine or continental Enokurra Sandstone shows that subsidence during sedimentation was considerable.

Origin and Deposition of the Yandanooka Group

The Yandanooka Group was derived from a terrain of granitic, meta-sedimentary and volcanic rocks. Most of the sediments are notable for the high proportion of volcanic fragments in them, and they have long been regarded as tuffaceous (Simpson and Glauert in Campbell 1910, p. 97; Woolnough and Somerville 1924; Johnson *et al.* 1954). Baker (1951) however was unable to find evidence of pyroclastic derivation for rocks he examined in the sequence stratigraphically below the Mt. Scratch Siltstone, and evidence cited in this paper supports his conclusions. The possibility that closer sampling of the Arrino Siltstone will reveal tuffaceous bands cannot, of course, be eliminated at present. The Mt. Scratch Siltstone is probably partly tuffaceous in origin. The volcanic fragments are commonly too altered for effective determination for their feldspar is cloudy, and ferromagnesian minerals have been replaced by iron ores and chlorite. Their composition ranges from microdiorite (andesite) to spilitic varieties.

Formations in the Yandanooka Group represent successively, from the base upwards, shallow water, probably littoral facies (Arrowsmith Sandstone); deeper water facies (Arrino Siltstone); shallow water or continental piedmont facies (Beaconsfield Conglomerate); shallow water or continental facies (Enokurra Sandstone); and a thick, fine-grained, partly tuffaceous facies, apparently deposited in fairly deep water (Mt. Scratch Siltstone).

The high proportion of labile constituents, such as feldspar and volcanic fragments, shows that the processes of mechanical disintegration dominated over those of chemical decay. The tectonic environment that best explains the petrography of this thick sequence is that of a sporadically subsiding basin bounded by a fairly rugged land surface. Some of the volcanism, at least, was contemporaneous with sedimentation.

The Enokurra Sandstone, unlike formations below and above it, contains no volcanic detritus. It was eroded from a granitic and meta-sedimentary provenance, and presumably came from a different direction from that of the other sediments. Its distinctive lithology, and the unconformity at its base, are best explained by sudden tectonism.

The areas from which the Yandanooka sediments were derived are not yet known. The nearest volcanic rocks are east of the Darling Fault near the Billeranga Hills, where intru-

sives lithologically like the microdiorite pebbles of the Beaconsfield Conglomerate have been mapped by Arriens and Lalor (1959). Their careful work has failed, however, to reveal spilitic rocks, although it is possible that they may eventually be found in the network of altered intrusions near the Darling Fault not investigated by them. They have mapped trachytes whose mineralogy was briefly discussed earlier (Glover 1958b), but no representatives of these distinctive rocks have been encountered in the Yandanooka Group. Abundant chert fragments would also be expected in the group if it had been derived from the sequence at present exposed in and near the Billeranga Hills, for considerable thicknesses of this resistant rock were found by Arriens and Lalor. If the volcanic detritus of the Yandanooka Group came from the east, it was presumably eroded from rocks that blanketed and concealed the present sequence. The Enokurra Sandstone, on the other hand, was derived from rocks very like those now exposed in the Mullingarra Inlier, and this is consistent with the evidence from cross bedding, which suggests a source to the north-west or north-north-west.

In view of the great thickness of sediments (about 30,000 feet of which remain) and the high proportion of volcanic material in most of them, extrusion must have been on a very large scale. It is conceivable that downwarping occurred partly as isostatic readjustment in response to the outpourings. The presence in the area of large faults (including the Darling Fault and the Urella Fault) is consistent with the tectonic picture suggested. There is, however, no undoubted evidence for their existence at the time of deposition of the group.

The Arrino Siltstone and Mt. Scratch Siltstone are notable for their red-brown to purplish colour in the field. There is no evidence at present to suggest that these formations are "Red Beds" in the normally accepted geological sense, and their deep colouration is believed due to surface oxidation (weathering) of their iron-rich, volcanically derived material. Examination of well cores or cuttings, however, would be necessary to demonstrate this.

Acknowledgments

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13.—Rainfall and Soil Control of Tree Species Distribution around Narrogin, Western Australia

By R. T. Lange*

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In an area around Narrogin, Western Australia, soils relate to erosional and depositional surfaces, and to rainfall. Tree species incidence also relates to the surfaces and to rainfall. Relationships between surfaces, soils, tree incidence and rainfall are presented. Evidence is also produced for species migrations and this is discussed in terms of the climatic and geomorphic history of the area.

Introduction

This report is of an autecological study of the relationships of twelve tree species to the rainfalls and soils in an area of transition in Western Australia, and concerns the extent to which these environmental factors and their histories control the tree distributions. The area of study (Figs. 1 and 2) surrounds the township of Narrogin (lat. $32^{\circ} 56' S.$ long. $117^{\circ} 11' E.$). It constitutes a rectangular strip of about 700 square miles between Cuballing in the north and Highbury in the south, from Williams in the west to Toolibin in the east, and is extensively cleared for agricultural purposes.

The Environment

Climate

The area occurs in a climatic zone of winter rainfall and summer drought (Gentilli 1956), and the rainfall distribution in the area is illustrated in Fig. 1. The annual precipitation decreases on a fairly even gradient from 25" of annual rainfall west of Williams to 15" per annum in the east of the area.

Geology

The parent rocks in the area are the Precambrian granites and gneisses of the West Australian Shield, with occasional basic intrusions (Wilson 1958).

Geomorphology and Soils

The relief and drainage in the area are shown diagrammatically in Fig. 2, which shows both drainage west to the sea, and east to the salt lake systems, hence the area includes elements of Jutson's Swanland and Salinaland physiographic divisions (Jutson 1955). According to Jutson, the lateritic peneplain or "old plateau" of Western Australia occurs in the former division as the Darling Plateau, and in the latter division as relicts, particularly in the form of mesas and buttes. Normal erosion in the stream-bearing Swanland division is not sufficiently advanced to obscure the old plateau, but Salinaland exhibits a new plateau of arid

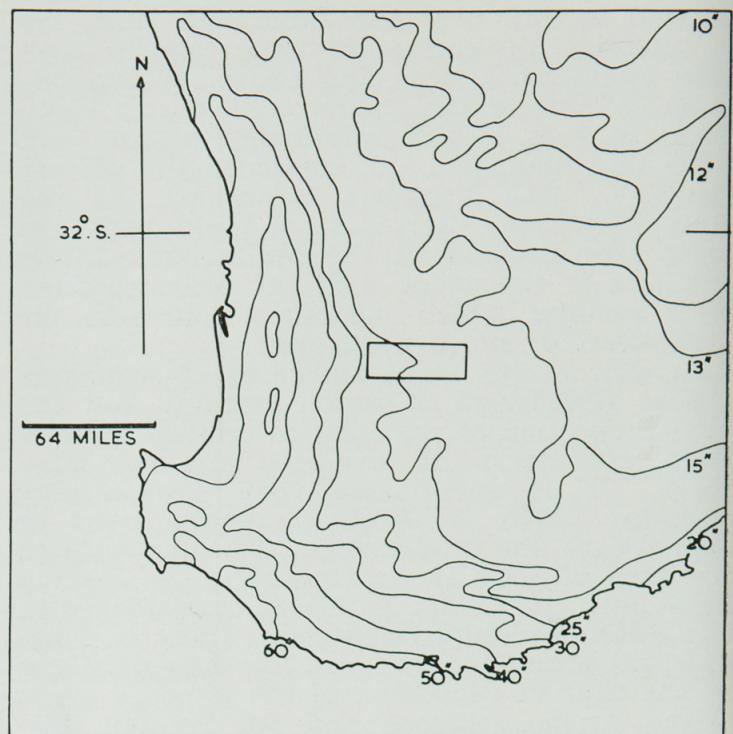


Fig. 1.—Locality plan and rainfall distribution.

erosion, and the boundary between the two divisions is the line separating rivers of the coast from interior drainage.

In the study area, drainage west occurs in relatively sharp valleys, while that to the east occurs in broad flat-bottomed ones, constituting western extensions of Jutson's "new plateau" of arid erosion. In the study area, the old plateau is largely destroyed, and is preserved only as residuals on the divides. At York, Mulcahy (1959) studied the soils of the old plateau, and the erosional and depositional surfaces resulting from its breakdown, and showed that the distribution of these surfaces determines the distribution of soils. A similar series of erosional and depositional surfaces occur in the study area, and although some have no described equivalents near York, most are the equivalents of surfaces described by Mulcahy.

The distribution of the surfaces themselves is controlled by the geomorphic history of the area, and the older surfaces are distinctly relicts left after the destruction of a great deal of their previous extensions. These latter have the bulk of their present distributions west of the study area. The oldest surface in the study area (Quailing erosional) is laterite, of Jutson's lateritic peneplain or "old plateau," but lateritic

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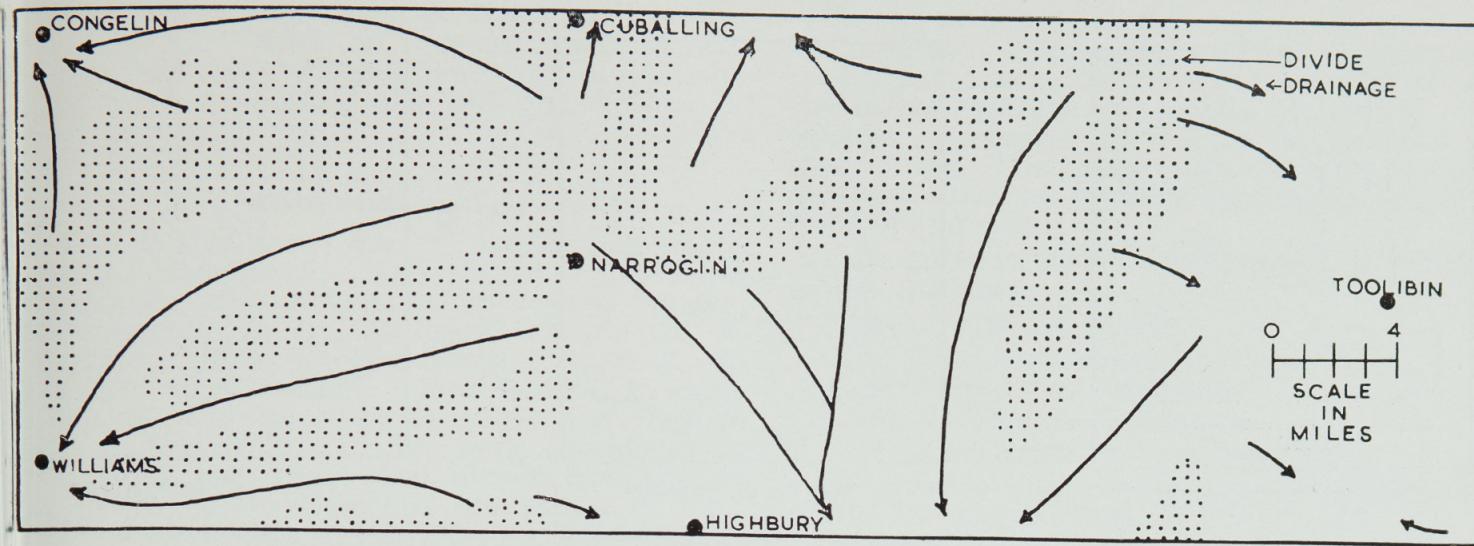


Fig. 2.—Relief and drainage.

profiles are not confined to the much modified old plateau preserved on the divides. They are found also as residual spurs and terraces on valley sides and floors respectively, representing an early phase of erosion cutting into the old plateau. Subsequent erosions and depositions have given rise to younger surfaces which carry soils developed on the truncated older lateritic surfaces, or, where more deeply cut, soils developed on exposed fresh rock.

This situation contrasts markedly with that pertaining in the high rainfall zone of the Darling Range, to the west of the study area. That area, although much dissected, carries laterite detrital material on valley sides and floors and this is often recemented such that nearly all soils are laterites. Thus laterites in the study area can be regarded as outliers.

In the east of the study area some of the younger laterites of valley sides were found to be calcareous. Considering the origin of laterite (Prescott and Pendleton 1952), this time must be secondary, i.e. brought in by wind or ground water. Laterite development followed by the occurrence of secondary lime clearly indicates formation in a wet climate, followed by relatively arid conditions.

In the study area, there is a close correlation between the surfaces and their associated soil types, and surfaces encountered in the area are listed below, against their topographical position and soil characteristics.

1) Surfaces located on divides.

Quailing erosional.—Massive residual laterite or heavy ironstone gravel.

Quailing depositional.—Deep yellow sands. Deposit derived from laterite.

Degraded Quailing erosional.—Laterite residuals reduced to a thin veneer of ironstone gravel over pale reddish clays resembling those of the Balkuling surface (q.v.).

Kauiring.—Grey sand over massive ironstone.

Monkopen.—Deep grey sand in depressions.

Granite outcrop and associated sandy deposits.—Shallow skeletal soils and associated deep sandy and gritty soils.

(2) Surfaces located on valley slopes and interfluves.

Belzunging.—Spurs and ridges carrying ironstone gravelly soils extending from the divides down towards the drainage lines. May be calcareous in the east of the area.

Breakaway face.—Pediments below the breakaways, carrying pale reddish and greyish clayey soils, often with a thin scree of ironstone gravel. May be calcareous in the east of the area.

Malebelling erosional.—Brownish gritty sands over yellow and red mottled weathered rocks.

Malebelling depositional.—Brown or greyish-brown gritty sands, often with a prominent bleached A₂ horizon over variously mottled weathered rock.

York.—Brown loams and loamy sands over reddish-brown clays. Close to drainage lines.

(3) Surfaces located on valley floors.

Avon.—Brown or grey clay at the surface.

Mortlock.—Lateritic valley terrace.

Truncated Mortlock.—Grey sands over domed clay. Often calcareous in deep sub-soil.

Sandy alluvium.—Brown sand over yellow clay. Not calcareous.

Flood plain sands.—Sandy deposits of braided stream pattern associated with the lake system in the eastern part of the area.

Baandee.—Resemble deposits at Baandee (Bettenay, priv. comm.). Fine textured calcareous aeolian deposits associated with lakes in the south-eastern part of the area.

(4) Fresh complex.

The situation pertaining in principal watercourses.

The outstanding edaphic discontinuity in the area occurs at the 20" annual rainfall isohyet, which marks the region of transition between external and internal drainage. Avon, Truncated Mortlock, Sandy Alluvium and Baandee surfaces of arid erosion occur in valley floors to the east of that isohyet only, together with all calcareous soils, and thus the 20" annual rainfall isohyet marks a pedocal-pedalfer boundary in the area. Calcareous soils occur to the

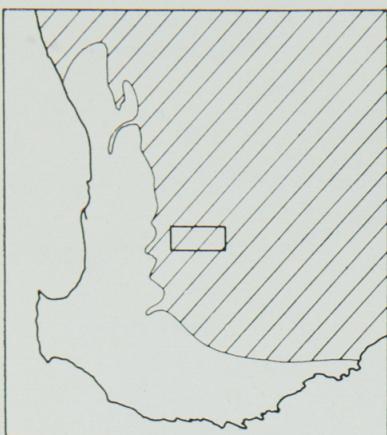


Fig. 3.—*A. acuminata*

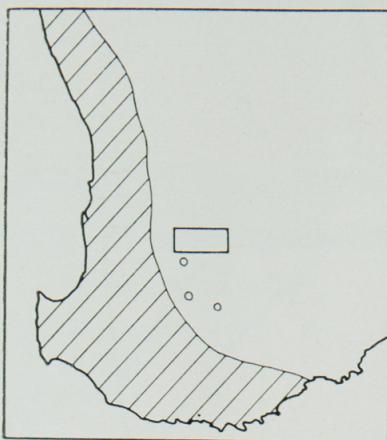


Fig. 4.—*B. grandis*

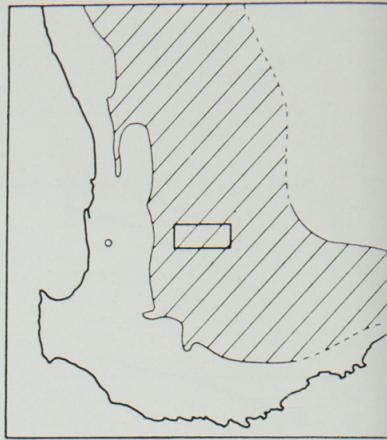


Fig. 5.—*C. huegeliana*

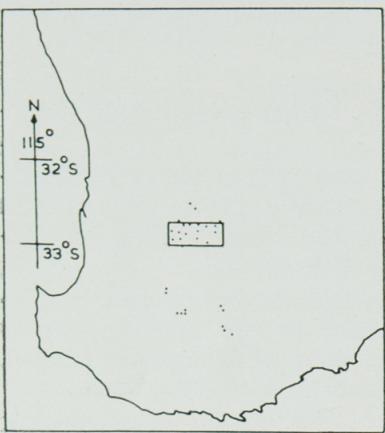


Fig. 6.—*E. astringens*

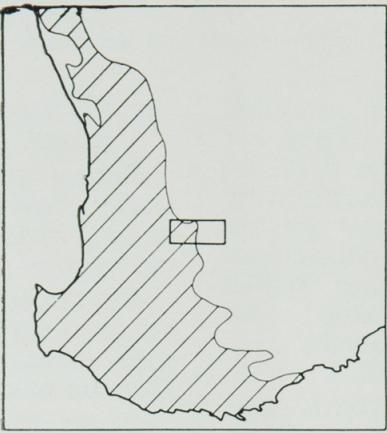


Fig. 7.—*E. calophylla*

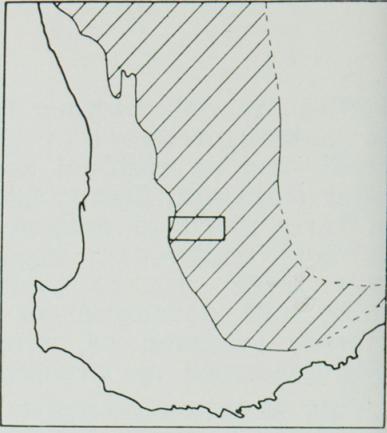


Fig. 8.—*E. loxophleba*

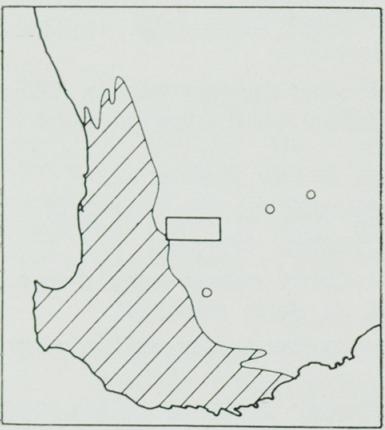


Fig. 9.—*E. marginata*

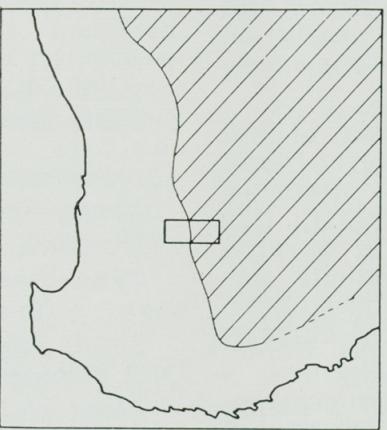


Fig. 10.—*E. longicornis*

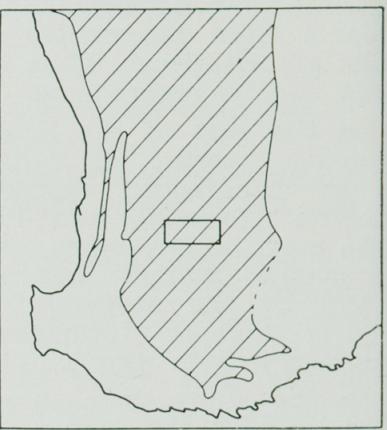


Fig. 11.—*E. redundans* var. *elata*

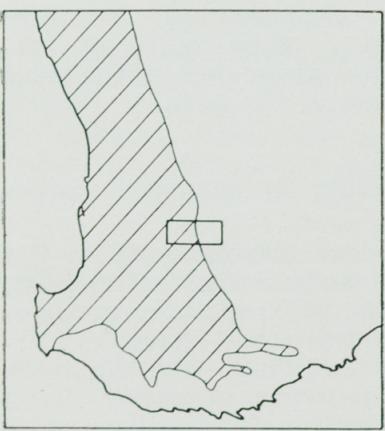


Fig. 12.—*E. rufida*

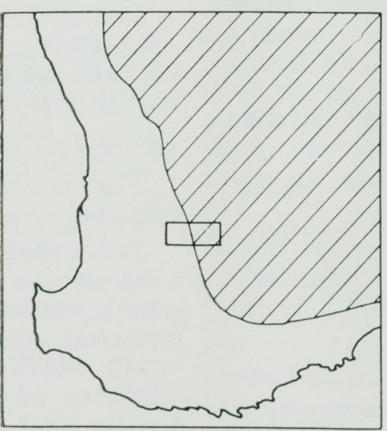


Fig. 13.—*E. salmonophloea*

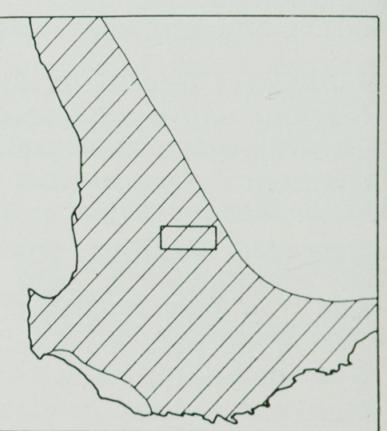


Fig. 14.—*N. floribunda*

Figs. 3-14.—Known distributions of the twelve tree species in south-western Australia (from unpublished data of Churchill and Storr).

east only, and occur even on some relict lateritic surfaces. Soils on western surfaces are characteristically without lime, and a relationship between rainfall and soil distributions is thus apparent.

Tree Distributions

The twelve tree species *Acacia acuminata* Benth., *Banksia grandis* Willd., *Casuarina huegeliana* Miq., *Eucalyptus astringens* Maiden, *E. calophylla* R. Br., *E. loxophleba* Benth., *E. marginata* Sm., *E. longicornis* F. v. M., *E. redunca* Schau. variety *elata* Benth., *E. rufa* Endl., *E. salmonophloea* F. v. M. and *Nuytsia floribunda* (Labill.) R. Br. were considered in this study, and their total known distributions in south-western Australia are shown in Figs. 3-14. Precise data of this kind are not available from published sources, and Figs. 3-14 have been drawn from unpublished surveys by D. M. Churchill* and G. M. Storr†.

Drastic changes in the distribution of tree species have occurred since the study area was cleared. Clearing commenced about one hundred years ago, and the arable land is now almost entirely cleared. Original distributions are now represented in skeletal patterns only, on fencelines and roadsides, in uncleared patches of arable and non-arable land, and in reserves. Clearing has resulted in rapid soil salinity changes (Teakle 1938) and current expansion of agriculture is resulting in the destruction of even relict distributions. *Santalum spicatum* (R. Br.) D.C. has been completely removed from the area by commercial cutters. By the use of a grid square-tree incidence system of plotting, the virgin distributional patterns of the 12 species were reconstructed,

Traverses were made throughout the area to view within two miles of any point, and the tree species incidence was recorded at intervals not exceeding one mile, on these traverses. Species-locality records from traverse data were plotted on maps of the area scaled at 4 miles to the inch and gridded in 2-mile squares, and grid squares were rated as positive if species-locality records occurred within them. Continuity of adjoining positive grid squares was taken as continuity of distribution, and two kinds of geographic distributions were recognised.

(1) *Continuous distributions.* Certain distributions exhibited continuity over an area exceeding 350 square miles and typically extending continuously across the boundary of the study area, with relatively high densities throughout grid squares. These distributions were termed *continuous*.

(2) *Disjunct distributions.* The remaining distributions exhibited continuity over an area not exceeding 30 square miles, and typically over a much smaller area, with relatively low densities, typically of single stands and often of only three or four trees. These distributions were termed *disjunct*.

Distributions of the twelve species in the area are presented individually in Figs. 15-26, where continuous distributions are plotted with closed circles representing the centres of positive grid squares. Disjunct distributions are located by open circles. The twelve species may be grouped on the similarities of their geographic distributions in the area:

(1) Species with continuous distribution across the area:

- (a) *Acacia acuminata*.
- (b) *Casuarina huegeliana*.
- (c) *Eucalyptus astringens*.
- (d) *Eucalyptus loxophleba*.
- (e) *Eucalyptus redunca* var. *elata*.

(2) Species with continuous distribution west of the 20" annual rainfall isohyet only:

- (a) *Eucalyptus calophylla*.
- (b) *Eucalyptus rufa*.

(3) Species with continuous distribution east of the 20" annual rainfall isohyet only:

- (a) *Eucalyptus longicornis*.
- (b) *Eucalyptus salmonophloea*.

(4) Species with disjunct distribution:

- (a) *Banksia grandis*.
- (b) *Eucalyptus calophylla*.
- (c) *Eucalyptus marginata*.
- (d) *Nuytsia floribunda*.

Comparisons with Figs. 3-14 places Figs. 15-26 in perspective. The study area lies in a zone of distribution margins and contains the eastern extension of some species of western distribution (*E. calophylla*, *E. rufa*) and western extensions of some eastern distributions (*E. longicornis* and *E. salmonophloea*). It brackets the distribution of *E. astringens* and falls within the distribution of *A. acuminata*, *C. huegeliana*, *E. loxophleba* and *E. redunca* var. *elata*. It also contains disjunct distributions, and these are all of species now distributed west of the study area.

Tree Distributions in Relation to Rainfalls and Soils

In south-western Australia there is no marked relief or climatic range, and it is recognized that plant distributions generally are controlled primarily by rainfall and soils (Gardner 1942). The total distributions of the 12 species (Figs. 3-14) illustrate this on comparison with the rainfall map (Fig. 1). Seven of the study species exhibit distributional margins in the study area. *E. calophylla*, *E. longicornis*, *E. rufa* and *E. salmonophloea* exhibit a fairly mutual boundary of distribution at the 20" annual rainfall isohyet and the related pedocal-pedalfer boundary. Disjunct distributions are all atypical of the rainfall relationships of their species in that they occur in lower rainfall areas. Thus the typical lower-rainfall limit for *E. calophylla* is 20" (Fig. 7), and the disjunct *E. calophylla* distribution at Toolbin occurs in a 15" rainfall. Similarly the disjunct distributions of *B. grandis*, *E. marginata* and *N. floribunda* occur in rainfalls below the typical lower limit for the species. However, all disjunct distributions east of the 20" isohyet are associated with the high ground-water effect (Mulcahy 1959).

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†Department of Zoology, University of Western Australia.

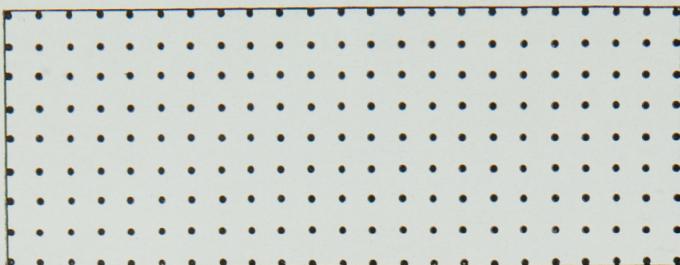


Fig. 15.—*A. acuminata*

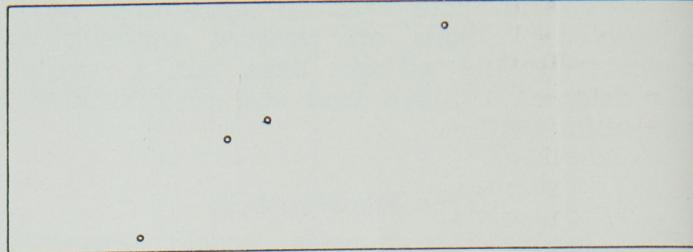


Fig. 16.—*B. grandis*

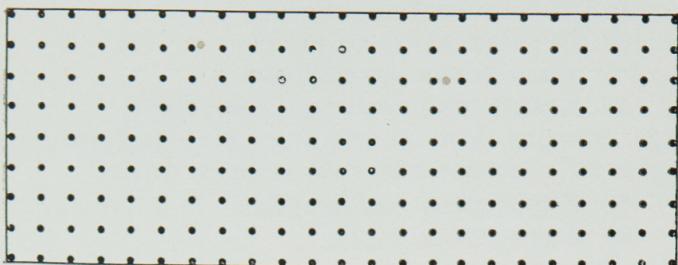


Fig. 17.—*C. huegeliana*

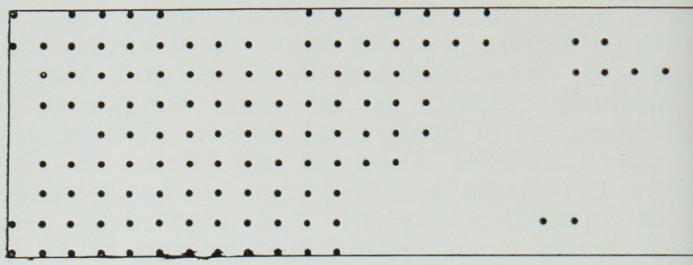


Fig. 18.—*E. astringens*

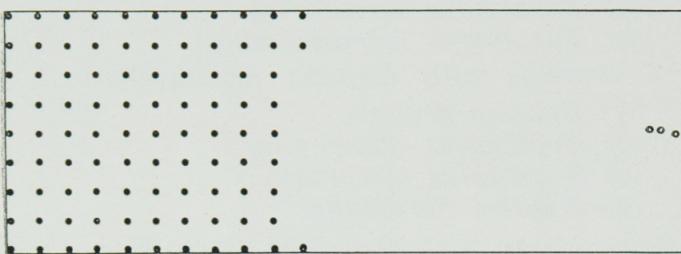


Fig. 19.—*E. calophylla*

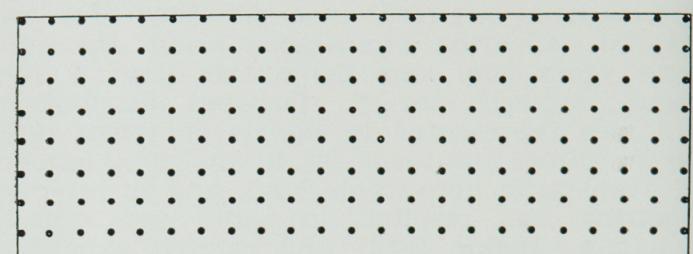


Fig. 20.—*E. loxophleba*

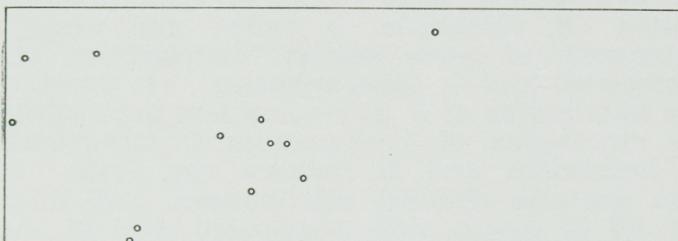


Fig. 21.—*E. marginata*

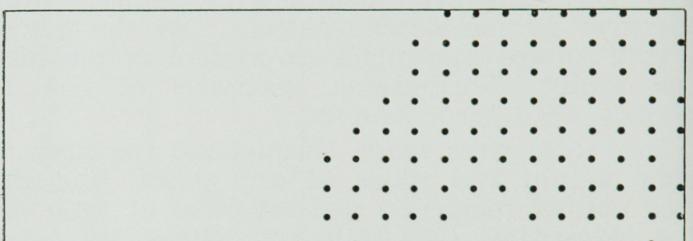


Fig. 22.—*E. longicornis*

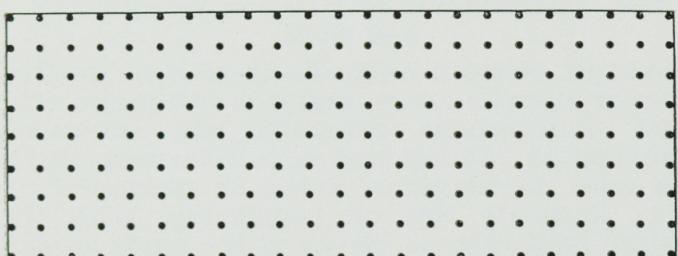


Fig. 23.—*E. redundans* var. *elata*

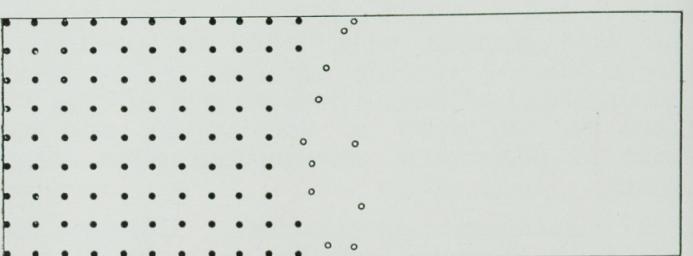


Fig. 24.—*E. rufa*

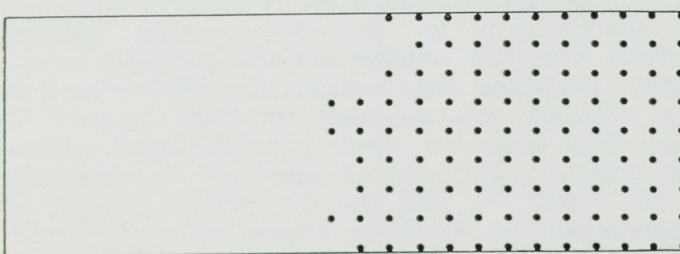


Fig. 25.—*E. salmonophloea*

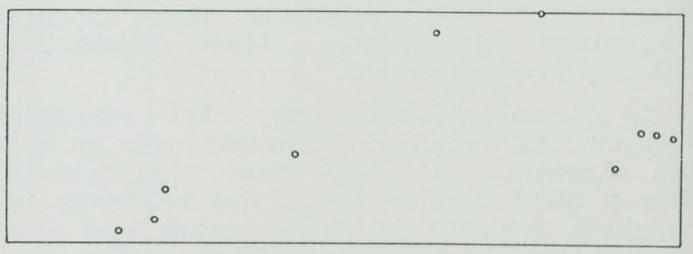


Fig. 26.—*N. floribunda*

Figs. 15-26.—Continuous and disjunct distributions of the 12 tree species defined in the study area. Symbols defined in text.

of the Monkopen deposits. It is notable that while such an effect may simulate conditions of high rainfall in a low rainfall area, there is no situation in the study area to simulate low rainfall in high rainfall regions.

The pedalfer-pedocal transition is the principal soil discontinuity in the area, and this occurs in the region of the 20" isohyet and the associated transition from internal to external drainage. This line marks the margins of continuous distributions of 4 species in the study area. Within the areas of pedalfers or pedocals, tree species exhibit specificities to surfaces and their associated soils, controlling local patterns of tree incidence. This control of distribution was not revealed by the grid system used to reconstruct the geographic distributions, and was studied by a point sampling procedure.

Surface determinations were made at each of 140 points distributed evenly across a broad median east-west transect of the area. Tree incidence on these surfaces was observed and species were scored as represented or not-represented at each point. Scores from the 140 points were listed as west or east of the 20" annual rainfall isohyet, to compare species in the areas where their continuous distributions overlap, and scores from the sites of disjunct stands were listed separately. Each of these lists was totalled, and tree incidence-surface interaction was detectable, i.e. certain species

never occurred on certain surfaces and certain species always occurred on certain surfaces. The various species exhibited a range of surface-specificities and conversely, surfaces varied in the numbers of species incident on them. These basic interactions are summarized in Table I, where an entry in the negative (-) signifies that the species so qualified never occurred on the surface referred to, at any of the sample points. Positive entry (+) signifies incidence of the species on the surface referred to, at one or more sample points.

Knowing the associated soils of the different surfaces, the relationships of the different species to the soils in the study area may also be summarized.

Nuytsia floribunda.—Restricted to deep sands derived from laterite and deposited in water-collecting hollows.

Banksia grandis.—Restricted to massive laterite, heavy ferruginous gravel or deep sands derived from laterite and deposited in water-collecting hollows.

Eucalyptus rufa.—Restricted to the situation pertaining in principal watercourses and to wet drainage lines in loams and gritty sands over mottled weathered rock.

Eucalyptus marginata.—Restricted to massive laterite or heavy ferruginous gravel, sometimes adjoining sands deposited in a water-collecting hollow.

TABLE I*

| | <i>E. marginata</i> | <i>B. grandis</i> | <i>N. floribunda</i> | <i>E. calophylla</i> | <i>E. rufa</i> var. <i>elata</i> | <i>A. acuminata</i> | <i>E. loxophleba</i> | <i>C. huuegiana</i> | <i>E. salmonophloea</i> | <i>E. longicornis</i> | <i>E. astringens</i> | <i>C. huuegiana</i> | <i>E. rufa</i> var. <i>elata</i> | <i>A. acuminata</i> | <i>E. calophylla</i> | <i>E. rufa</i> | <i>E. loxophleba</i> | <i>E. astringens</i> |
|---|---------------------|-------------------|----------------------|----------------------|----------------------------------|---------------------|----------------------|---------------------|-------------------------|-----------------------|----------------------|-----------------------|----------------------------------|---------------------|----------------------|----------------|----------------------|----------------------|
| + | - | - | - | - | - | - | - | - | - | - | - | Avon | - | - | - | - | - | - |
| + | - | - | - | - | - | - | - | - | - | - | - | Baandee | - | - | - | - | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | Breakaway face | - | + | - | - | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | Floodplain sands | + | - | + | - | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | Granite outcrop | - | + | - | + | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | Monkopen | - | - | - | - | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | Balkuling | + | - | - | - | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | Belzunging | + | + | - | - | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | Quailing erosional | + | - | + | + | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | Granite sandy soils | + | + | - | + | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | York | + | + | + | - | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | Quailing depositional | + | + | - | + | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | Mortlock | + | + | + | - | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | Quailing residual | + | + | - | + | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | Truncated Mortlock | - | - | + | - | + | - |
| - | - | - | - | - | - | - | - | - | - | - | - | Mortlock | + | + | + | + | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | Belzunging | + | + | + | - | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | Sandy alluvium | + | + | + | + | + | - |
| - | - | - | - | - | - | - | - | - | - | - | - | Balkuling | - | - | - | - | - | - |

* The relationships between surfaces and soils and between surfaces and tree species incidence, described in this paper, do not necessarily apply beyond the study area. For example, on traverses between York and Quairading where essentially similar surfaces occur, *E. salmonophloea* occurs on Balkuling surfaces that are neither calcareous nor derived from basic materials.

Eucalyptus astringens.—Restricted to degraded Quailing, Balkuling and breakaway surfaces. The soils are pink or white weathered rock usually with a scree of ferruginous gravel.

Eucalyptus salmonophloea.—Occurs on valley clays, or sands over domed clays, calcareous or calcareous at depth. It also occurs on those lateritic surfaces which contain secondary lime.

Eucalyptus calophylla.—Occurs principally on non-calcareous sandy soils and on laterite within its continuous distribution. Its relict representation at Toolibin is on relict deep sand deposited in a water-collecting hollow.

Eucalyptus loxophleba.—Occurs on brown gritty sands over mottled weathered rock, on lcambs, and on calcareous clays and sandy soils. It occurs on those lateritic surfaces which contain secondary lime.

Eucalyptus longicornis.—Occurs principally on calcareous soils associated with valley floors and salt lakes, but occurs also on calcareous laterites and on soils of the Balkuling surface derived from basic parent materials.

Acacia acuminata.—Occurs on various soils, particularly sandy alluvium, loam and granitic skeletal soils. It does not occur on very calcareous clays and sands, or on massive laterite, breakaways, heavy ferringinous gravel or deep sands.

Casuarina huegeliana.—Occurs on various soils, particularly granitic skeletal soils and associated sands but not on very calcareous clays and sandy soils, or on loams or breakaways.

Eucalyptus redunca var. *elata*.—Occurs on many soils, but not on very calcareous sands and clays, or on granitic skeletal soils.

Discussion

The two environmental factors of rainfall and soils have a marked influence on tree distributions in the study area, and the occurrence and distribution of the different soils themselves relates to rainfall, which has brought about soil changes in geological time. In the area studied, margins of continuous tree distributions, the pedalfer-pedocal boundary and the 20" rainfall isohyet all relate closely. Within areas of continuous tree distributions, incidence patterns relate closely to local soil patterns. Only disjunct tree distributions on soils of some *relict* surfaces do not relate to present rainfall. This is not altogether inconsistent, however, as a high ground-water effect simulates high rainfall conditions in many of these instances, and there is evidence that disjunct distributions relate to past rainfall distribution.

All detected disjunct tree distributions are of species now otherwise distributed west of, or in the west of the study area, in regions of relatively high rainfall. In the case of *E. marginata*, disjunct stands complete a line observed to extend from areas of continuous distribution west of the study area to outliers at Jilakin Rock and Hyden. Similarly, *E. calophylla* and *B. grandis* exhibit eastern disjunct and western continuous distribution. Tree species now distributed continuously east of the 20" isohyet do not exhibit western outliers.

Disjunct tree distributions are located on old lateritic soils on or derived from Jutson's

"old plateau." This was considered to have had broad distribution as a peneplain under conditions wetter than the present and favourable to laterite formation, and to have undergone subsequent arid erosion, resulting in its partial destruction in the interior (Jutson 1955).

Wet climate of the kind necessary for laterite formation has certainly changed in nett effect towards arid conditions, indicated by secondary deposition of lime in relict lateritic surfaces in the east of the study area.

With increase in aridity, the original rainfall and edaphic conditions have retreated westwards, and the sites of disjunct vegetation stands are *relicts* of the original conditions, where high soil-water availability substitutes for rainfall. Aridity permits accumulation of lime, and calcareous soils have extended westwards on the surfaces of the new plateau. Even some relict lateritic surfaces have become calcareous under the drier conditions, and calcareous surfaces have been occupied by species which have migrated westwards as a result.

According to Crocker (1959), who recently summarized the known history of vegetation and climate in Australia, peneplanation and apparent humid climate of the Tertiary limited habitat diversity in Australia, and relatively humid times may have persisted to the early Recent with some arid periods. Subsequent severe aridities in the late Quaternary eliminated many vegetational units and resulted in the retraction of others to more favourable situations. Since that time there has been expansion. The genera studied here, with the exception of records for *Nuytsia*, were apparently all established by the end of the Tertiary.

The simplest hypothesis accounting for the disjunct distributions in the study area is that the species involved had continuous distributions over the area, under the rainfall and soil conditions preceding the most recent aridity.

Acknowledgments

The writer would like to express his thanks to Professor E. J. Underwood and Dr. C. A. Parker, who made this work possible; to Mr. M. Mulcahy for his assistance in the field, and to Mr. D. M. Churchill and Mr. G. M. Storr for the data for Figs. 3-14.

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To bring rain and supply baby spirits a *Wandjina* painting was retouched, normally just before the wet season was due to begin. The increase of animal and plant species was achieved by the retouching at the same time of their representations in the gallery. In the providing of baby spirits the *Wandjina* is fused with the rainbow serpent, *Ungud* or *Galeru*. The rainbow serpent lives in water holes and is believed to bring spirit babies to these pools, from which they are incarnated by the retouching of the *Wandjina* paintings. The rainbow serpent is also depicted in some *Wandjina* galleries.

True *Wandjina* paintings have previously been thought to be restricted to the territory of the Ungarinyin, Worora, Wunambul, Gwini and Gulari Tribes of the North Kimberley (Elkin, 1930, 1948, 1954; Capell, 1939; Schulz, 1956; Worms, 1955), though McCarthy (1957, 1958) points out that paintings somewhat similar to the *Wandjina* and *Galeru* occur as far east as Arnhem Land in the Northern Territory. Capell (1939) observed that the Unggumi Tribe had typical *Wandjina* myths, but he understood that

they did not have the paintings. However we now know that they do in fact possess *Wandjina* paintings in the numerous limestone caves of the Napier Range, near the southern border of their tribal territory. Moreover the Kuniandi, Bunaba, and Gidya Tribes also have painting of the *Wandjina-Galeru* type.

The distribution of the various tribes of the West Kimberley region with whom I have had contact is shown on Fig. 1, together with the locations of the various rock paintings described in this paper. The tribal boundaries were obtained from discussions with many members of the various tribes. Even so they can only be regarded as approximate, as the exact boundaries of the tribes prior to settlement by the white man are no longer well-known to the Aborigines.

I would like to express my sincere thanks to Professor A. P. Elkin, with whom I corresponded on the subject of the paintings. His valuable encouragement and advice were largely instrumental in causing me to prepare this paper.

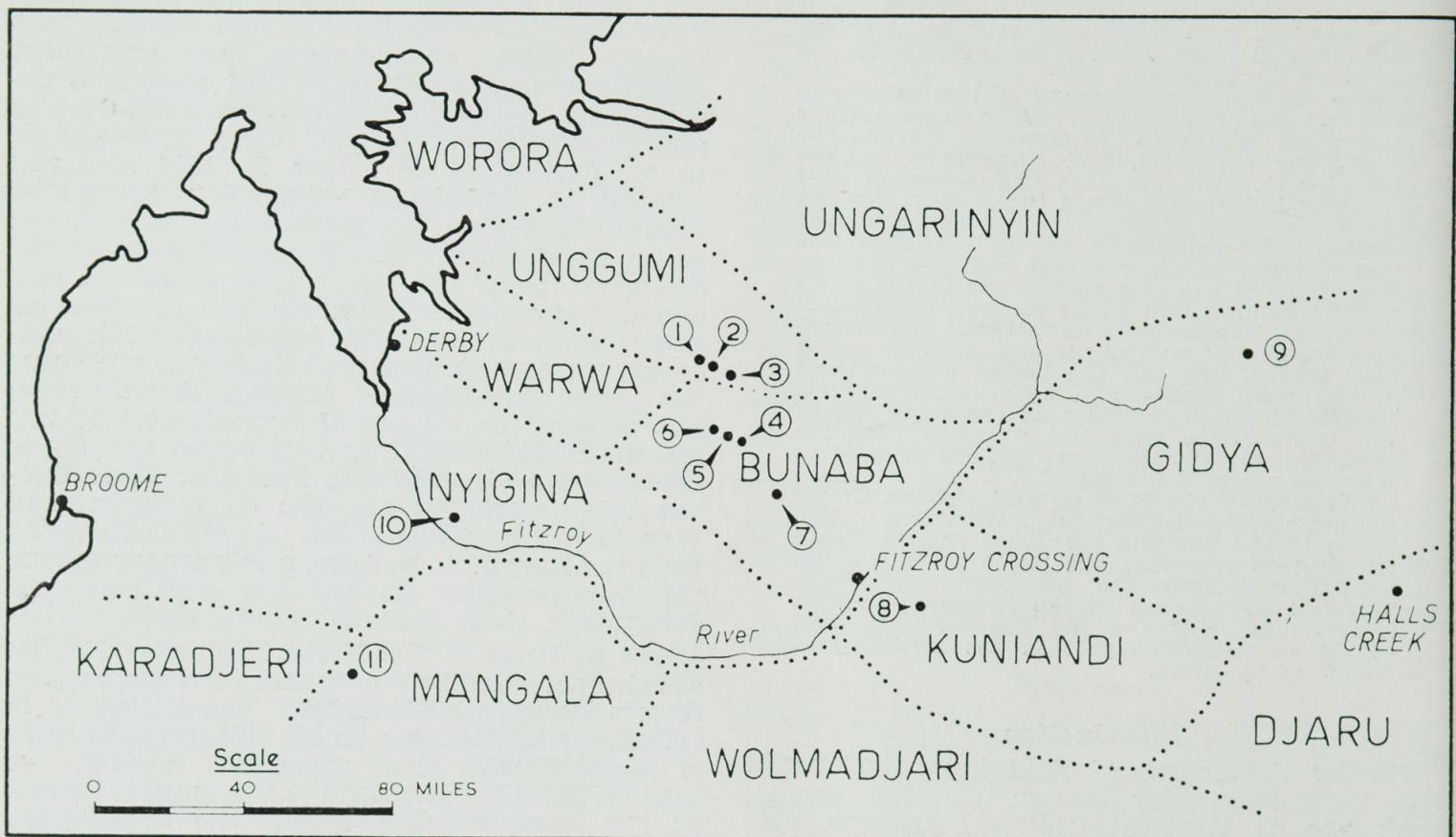


Fig. 1.—West Kimberley Region Showing Aboriginal Tribal Territories and Rock Painting Localities.

1. Cave beside Burrallumma Spring, $4\frac{1}{2}$ miles east-north-east of the eastern entrance to Windjana Gorge.
2. Cave 300 yards south-east of the eastern entrance to Windjana Gorge.
3. Cave between Windjana Gorge and Carpenters Gap, about 1 mile from the gap, on the north side of the Napier Range.
4. Cave $\frac{1}{4}$ -mile south-east of Elimberrie Spring, on the north side of the Oscar Range.
5. Cave $2\frac{1}{4}$ miles west-north-west of Elimberrie Spring.
6. Rock shelter at the foot of the cliffs $3\frac{1}{2}$ miles west-north-west of Elimberrie Spring.
7. Cave beside Linesman Creek, on the south side of the Oscar Range, 4 miles north-west of 12-mile bore.
8. Cave in Menyous Gap, 20 miles south-east of Fitzroy Crossing.
9. Cave about 2 miles west-north-west of Elgie Cliffs homestead.
10. Rock shelter on the west side of Mt. Anderson, $2\frac{1}{2}$ miles north-west of the station homestead.
11. Cave about $\frac{1}{2}$ -mile south-west of Dampier Downs homestead.

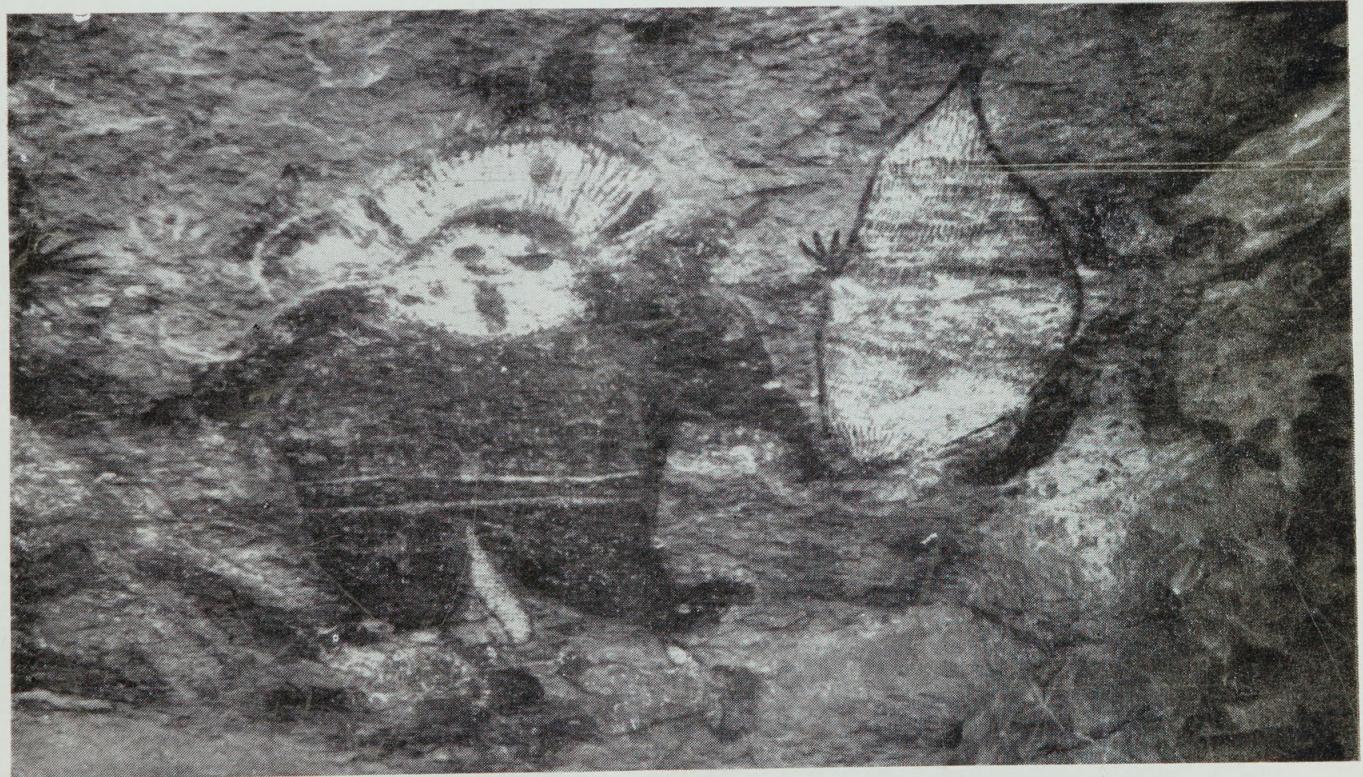
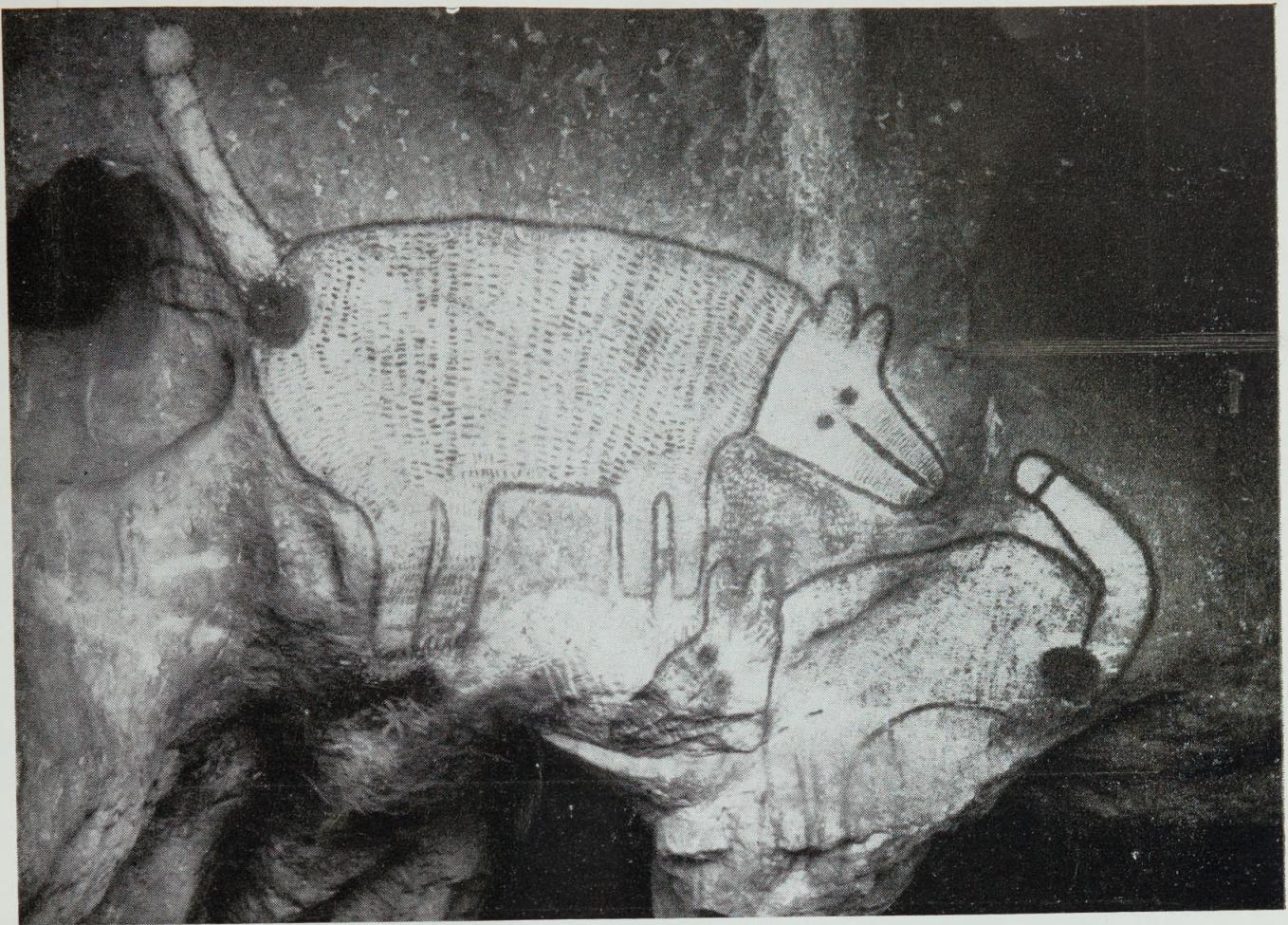
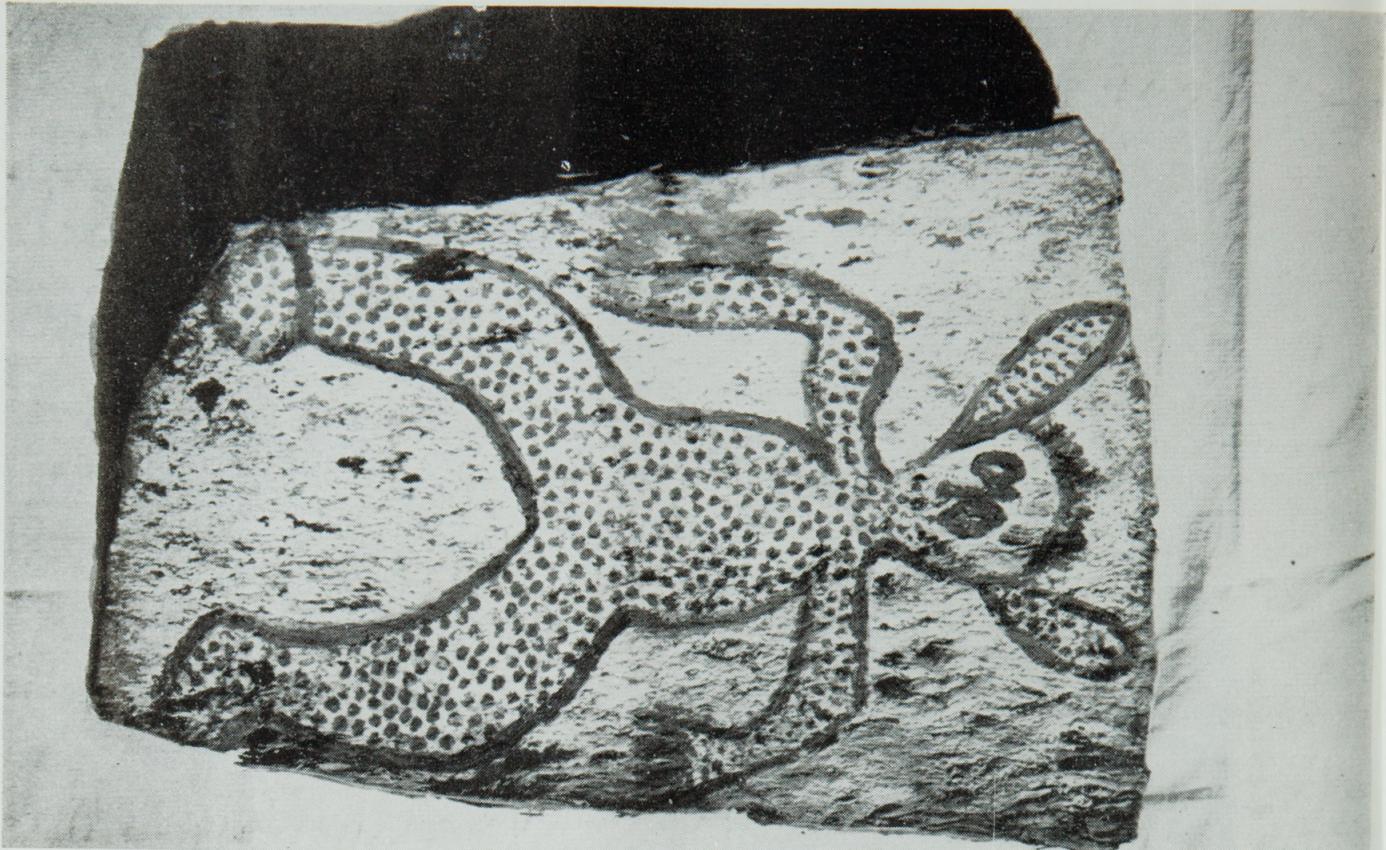


PLATE I

Fig. 1.—Dingo paintings near Burrallumma Spring, in Unggumi tribal territory. Map locality 1.
Fig. 2.—Wandjina, yam, and (?) "lightning men" paintings, near the eastern entrance to Windjana Gorge. Note the two small human figures painted beneath the Wandjina. Map locality 2.

1



2

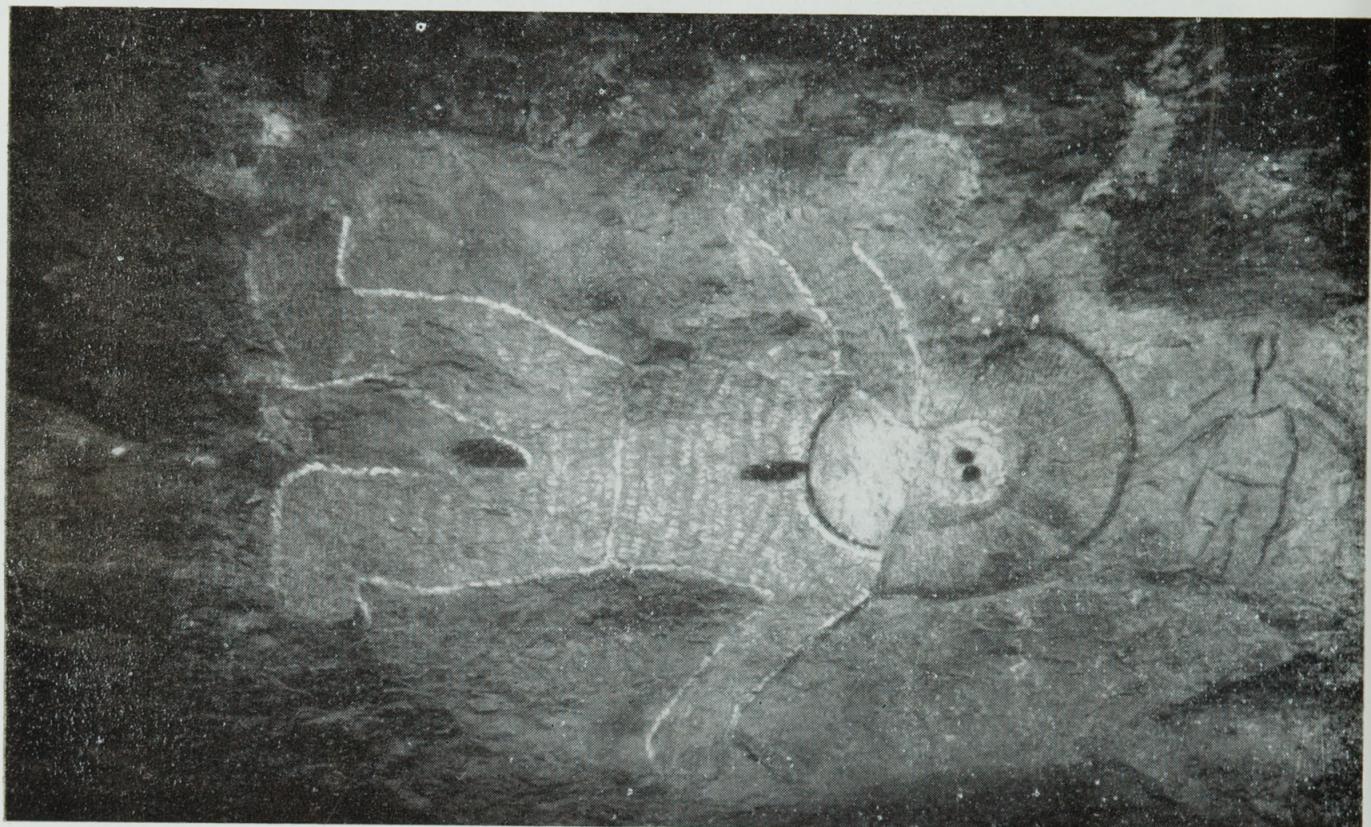


PLATE II

Fig. 1.—Bark painting of *Nura Nura*, the "lightning man." Worora Tribe, Mowanum Mission, Derby.

Fig. 2.—*Wandjina* painting in Unggumi tribal territory, between Carpenters Gap and Windjana Gorge, on the north side of the Napier Range. Note the small female *Wandjina* beside the main figure. Map locality 3.

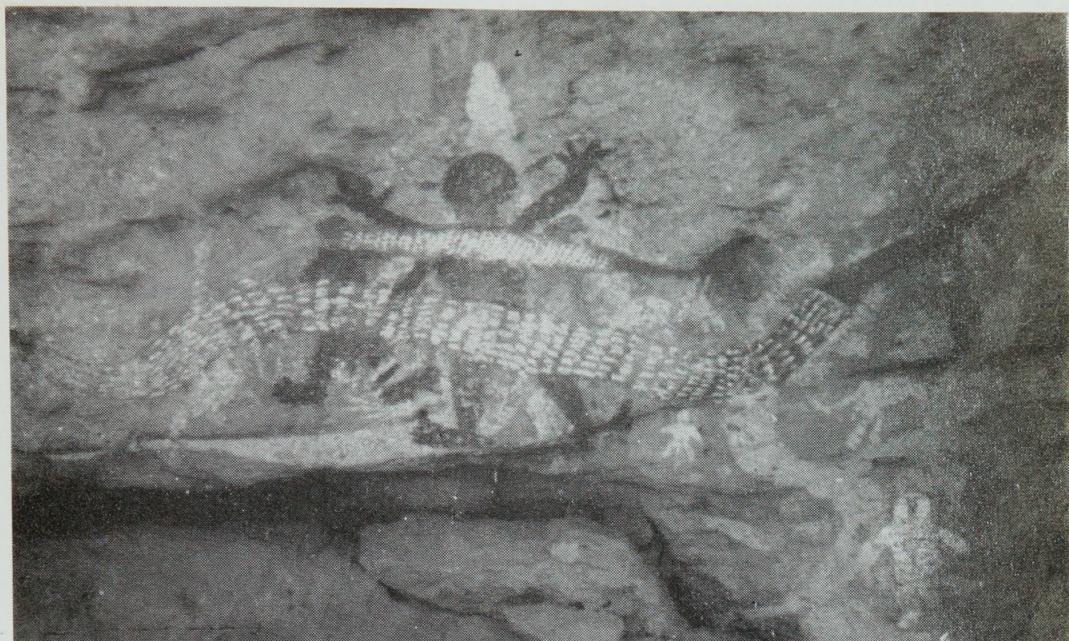
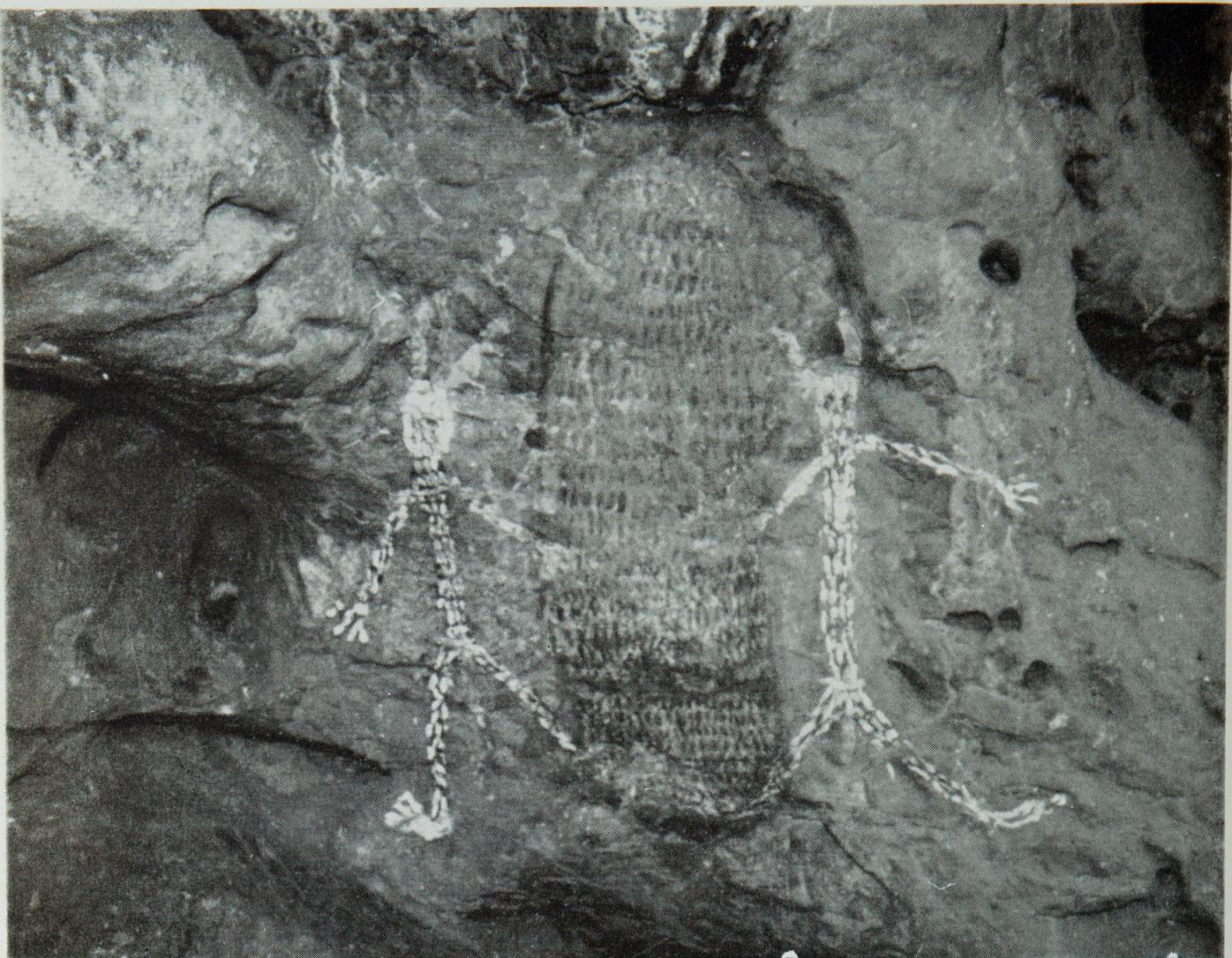


PLATE III

Fig. 1.—Paintings near Elimberrie Spring, in Bunaba tribal country. Shows the rainbow serpent (*Ungerooroo*), a probable "lightning man," and various smaller figures. Map locality 4.
Fig. 2.—Nurunguni-Nowungoo paintings. Map locality 6.

1



2



PLATE IV

Fig. 1.—Paintings of "stick-men" or "lightning men," on each side of a yam. Map locality 6.

Fig. 2.—Paintings of a Bungarra lizard and an eel, $\frac{1}{4}$ -mile south of map locality 6. Bunaba tribal territory.

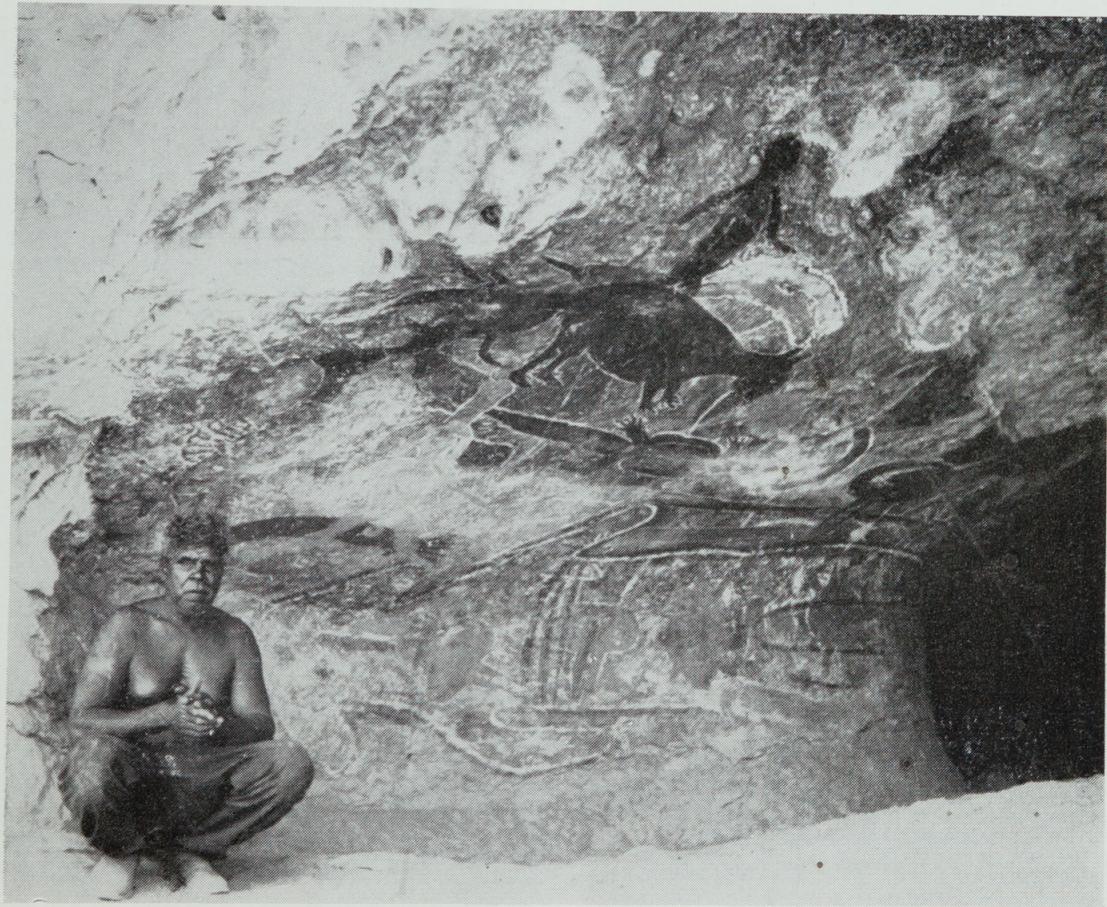


PLATE V

Fig. 1.—Nurunguni figures in a cave beside Linesman Creek, on the south side of the Oscar Range. Bunaba tribal territory. Map locality 7.

Fig. 2.—Nurunguni paintings at Menyous Gap, in Kuniandi tribal country. Map locality 8. The main figure, which is shown lying on its side is of *Nurunguni-Gnarboo*, the All-Father. Other paintings depict *Nurunguni-Junba*, the arm of *Nurunguni-Gnarboo*, emus, a crocodile, a kangaroo, a spirit child, clouds, falling rain, and a boomerang.

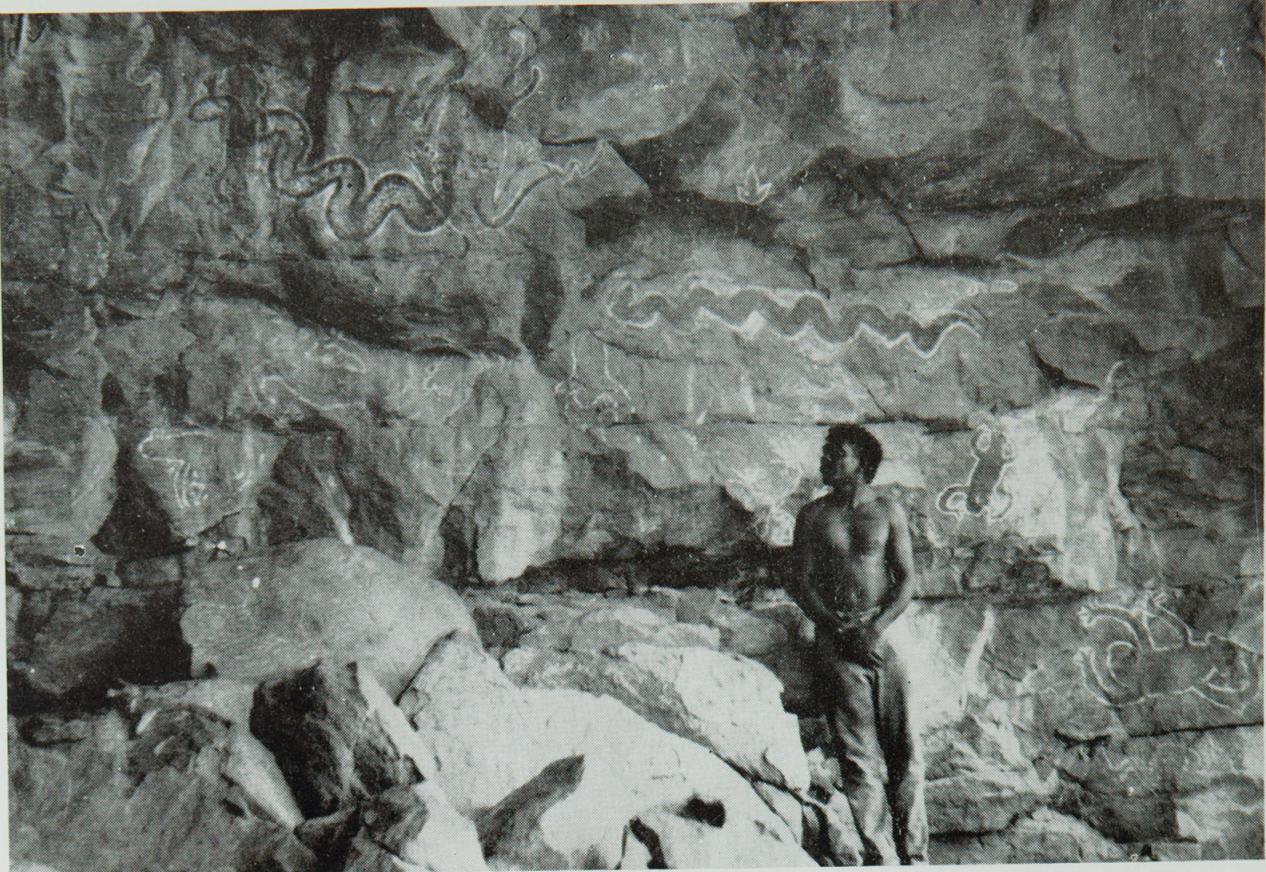


PLATE VI

Fig. 1.—Cave gallery near Elgie Cliffs homestead, in territory of the Gidya Tribe. Map locality 9. The *Nurunguni* figures include snakes (probably the rainbow serpent), frogs and a wallaby.

Fig. 2.—Paintings in a cave in Mangala country, near Dampier Downs homestead. Map locality 11. The designs symbolize the journeys of the All-Father during the primeval dream-time. Note also the small human figure on the right.

The Rock Paintings

The rock paintings described in this paper occur in the tribal territories of the Unggumi, Bunaba, Kuniandi, Gidya, Nyigina, and Mangala Tribes.

Unggumi Tribe

Paintings have been studied from three localities in Unggumi country, on the northern side of the Napier Range near Windjana Gorge. This gorge is one of the most impressive physiographic features of the Kimberley District. It is formed where the Lennard River has cut through the limestones of the Napier Range, 70 miles east of Derby. On the southern side of the Napier Range the territories of the Unggumi and Bunaba Tribes met at Windjana Gorge, but on the northern side of the range the Unggumi extended several miles east of the gorge. The Bunaba name for the gorge is "Talay," and on most maps of Western Australia it is called "Devils Pass," a name which is probably due to some "devil-like" Aboriginal paintings in a cave near the eastern entrance to the gorge. Other paintings are known 4½ miles east-north-east of the gorge and between the gorge and Carpenters Gap.

Burrallumma Spring.—On the north side of the Napier Range, 4½ miles east-north-east of Windjana Gorge, there is a permanent freshwater spring, known to the Aborigines as Burrallumma (map locality 1). In a small limestone cave 25 yards west of the spring there is an impressive painting of two large dingoes (Plate I, Fig. 1). The paintings are 8 feet wide, and are executed in white clay, red ochre, yellow ochre, and charcoal. Both animals are shown defecating, and the anus of each is strongly outlined in brilliant red ochre. Other small paintings are drawn around the dingoes, including stars (*windinya*), the bardi grub, small men, and a number of shapeless unidentified objects. The general name used by the Unggumi for such rock paintings is *Manjimanjigardingi*.

Unfortunately full details of the myth connected with this painting now appear to be lost. Only two male members of the Unggumi Tribe are alive today. I interviewed Paddy (*Dijul*), the older of these two men, but he had never visited this cave, though he knew of its existence. He later confirmed the story about the paintings given to me by an old Ungarinyin man named Napier Paddy (*Pandamarra*). This man has lived most of his life on Napier Downs Station in Unggumi tribal country, and he had visited the cave several years before with old Unggumi men. It appears that the two dingoes (called *kia*) came from the Leopold Downs area, where they were responsible for clearing all the trees from the wide black-soil plains, during the far-off dream-time (*Ungud*). They travelled along the north side of the Napier Range to Burrallumma, where they dug a deep hole which they filled with water to form the present spring. Following this they went to the nearby cave and turned into paintings. The reason why the dingoes are shown defecating was either not known by my informant or he was unwilling to tell. He

did not know the mythological significance of the other smaller paintings in the cave.

Windjana Gorge.—In the limestone cliff about 300 yards south-east of the eastern entrance to Windjana Gorge, there is a large cave following a bedding plane in the limestone (map locality 2). It is decorated by numerous paintings of men and animals, the main feature being a large male *Wandjina* figure 6 feet 9 inches high, standing upright (Plate I, Fig. 2). He is drawn in white clay and red ochre, and shows most of the features of the *Wandjina* paintings of the Worora and Ungarinyin, including the horseshoe-shaped band around his head, and the lack of a mouth. However unlike *Wandjinjas* of these tribes his sex is clearly indicated. Two small figures beneath his feet may be his children. On his left-hand side are two devil-like figures with long ears and upstretched hands, painted in red ochre, on each side of a large *yam*. Similar "devils" are painted in other parts of the cave. It seems very likely that each of these figures is of a "lightning man," though I was unable to confirm this. The Worora paint similar figures which they call *Nura Nura*, "the lightning man," the main feature of this person being his long ears (see Plate II, Fig. 1). *Nura Nura* is believed to be responsible for the lightning during the closing stages of a rain storm. Other paintings in the cave include a dingo, further human figures, crocodiles, and several stencilled hands.

I was unable to learn much about this gallery from the natives, though several knew of its existence, and one Bunaba man told me that his hand was stencilled there. The Unggumi use the name *Wandjina* to describe the main figure in the cave, and I was told that his main function was to bring the rain every wet season. My Unggumi informant told me that in addition to touching up the painting it was necessary to break a certain tree near the *Wandjina* cave in order to bring rain.

Below the *Wandjina* cave is another cave with a smoke-blackened roof and a clay floor, which may serve as a good site for archaeological excavations, both for Aboriginal and animal remains. It is interesting to note that the bones of the giant extinct marsupial *Diprotodon austalis* were found in gravels near the western entrance to Windjana Gorge by the first geologist to visit the area (Hardman 1887).

Between Windjana Gorge and Carpenters Gap.—About 2 miles east-south-east from Windjana Gorge, on the north side of the Napier Range, is another large cave containing a typical male *Wandjina* figure (map locality 3). The cave is about 1 mile from Carpenters Gap, and is in Unggumi tribal territory.

The *Wandjina* is shown lying on his side and is 5 feet 9 inches long (Plate II, Fig. 2). He is painted in orange and red ochre, white clay, and charcoal, and has eyes but no nose or mouth. Beside his head is a small female *Wandjina*. A few other poorly executed paintings occur in this cave, and there are numerous grooves cut in the limestone rocks, the purpose of which is not known.

I could not locate any natives who knew this cave, though I was assured that it must be in

original Unggumi country. Further paintings in the area once occupied by this tribe along the Napier Range have been noted by other geologists, but I have not been able to visit them.

Bunaba Tribe

The Bunaba Tribe occupied the country west of the Fitzroy River around Fitzroy Crossing, the Oscar Range, the northern end of the Napier Range, and the southern part of Leopold Downs Station.

Numerous caves and rock shelters occur in the limestones of the Napier and Oscar Ranges, and many are decorated with paintings. The Bunaba deny that these are actually paintings, and refer to them as *Nurunguni* or, less often, *Djeralli*. The *Nurunguni* are said to be men and animals who inhabited the world during the far-off dreamtime and who left their images in caves (*Nowani*) after their journeyings were over. *Nurunguni* is also a name for the dreamtime, other expressions for this primeval period in the Bunaba language being *Ungud* and *Djurda*, terms which are also common to the Unggumi tongue. Bunaba men told me that even prior to white settlement the paintings were never touched up by natives, in fact several of them told me severely that to touch any of the *Nurunguni* would result in the crippling of the offending limb.

Typical *Wandjina*-type paintings occur in Bunaba territory, and these are referred to as *Nurunguni-Nowungoo*. *Nowungoo* is the Bunaba word for father, and the figure represented in the paintings is supposed to be the All-Father, who journeyed through the tribal territory during the far-off dreamtime creating the physical features of the country. With him were the first representatives of the various animal and plant species. At the end of their journeying they went to the caves and rock shelters, leaving their images in the rock. I was told that there was only one All-Father, but he left his image in a number of different localities. There does not seem to be any clear connection between the *Nurunguni-Nowungoo* and rainmaking, even though he is shown as a typical *Wandjina*. Moreover I was told that his horseshoe-shaped headdress is the rainbow. Rain-making was achieved in the Bunaba Tribe by means of "rain stones."

The rainbow serpent forms an important part of Bunaba mythology. He is generally referred to as *Ugeroo*, but is sometimes called *Galeru* or *Ungud*. He is believed to have made the water-holes, and his present function is to keep up the supply of spirit children in these water-holes, from which they can be incarnated through the "dreams" of their fathers.

Numerous paintings have been found in the Oscar Range, and only the more interesting of these will be described here.

1/4-mile south-east of Elimberrie Spring.—Elimberrie is a well-known permanent spring on the north side of the Oscar Range. A large cave is present in the limestone just to the south-east of the spring (map locality 4), and this is decorated with numerous Aboriginal paintings. The main figure is that of a man about 5 feet tall, painted entirely in red ochre, and having long ears. He is probably a "lightning man,"

equivalent to *Nura Nura* of the Worora. Another smaller "lightning man" is present in another part of the cave, and is overpainted by a rainbow-serpent (*Ugeroo*), in red ochre and white clay, which is 5 feet 9 inches long (Plate III, Fig. 1). Another smaller rainbow serpent is present above it, and there are several other paintings nearby, including a small figure which is probably that of a spirit child.

2 1/4 miles west-north-west of Elimberrie Spring.—At this place (map locality 5) there is a small cave with numerous paintings of *Ugerco*, the rainbow serpent, together with small human figures. They are painted in white clay and red and yellow ochre. Some of the small human figures show a "rainbow" headdress. Several stencilled hands occur in the cave, and there is one stencilled boomerang.

3 3/4 miles west-north-west of Elimberrie Spring.—The cliffs which mark the north side of the Oscar Range in this area are almost vertical, and are 250 to 300 feet high (map locality 6). There are a number of rock shelters at the foot of these cliffs, and some of them are decorated with *Nurunguni* paintings. The best locality is *3 3/4 miles west-north-west of Elimberrie*. It contains large numbers of paintings, many of them well-executed, the most striking figure being that of *Nurunguni-Nowungoo*, drawn in white clay, charcoal, and red ochre (Plate III, Fig. 2). The painting stands 4 feet high, and closely resembles the *Wandjina* paintings of the northern tribes. He has no mouth, but there is a strange horizontal line drawn between the eyes and nose, the meaning of which I have not determined. A series of lines in red ochre are shown radiating from his rainbow headdress. Similar lines in *Wandjina* paintings of the Ungarinyin Tribe are regarded as the hair. A further representation of *Nurunguni-Nowungoo* is shown in the shelter, drawn in white clay over an older figure in red ochre. Numerous other human figures are present, including two "stick-men," painted in white clay, on each side of a yam (Plate IV, Fig. 1). The men have long ears and may be "lightning men"; the representation strongly resembles that in the cave near the eastern entrance to Windjana Gorge in Unggumi country (Plate I, Fig. 2).

The rock shelter also contains representations of crocodiles, a kangaroo, and various other animals, together with numerous stencilled hands.

In the rugged limestone country $\frac{1}{4}$ -mile south of the rock shelter there are a number of other paintings at the foot of a smooth massive outcrop. They are of a Bungarra lizard and an eel (Plate IV, Fig. 2) together with small human figures, all painted in red ochre.

Linesman Creek.—An impressive series of paintings occur in the small gorge cut by Linesman Creek, on the south side of the Oscar Range, 4 miles north-west of 12-mile bore (map locality 7). The paintings stare out over the gorge from a cave 40 feet up in the eastern limestone wall. The cliff-face in front of the cave can only be ascended with great difficulty. I managed to do so, but could not get down again until a rope was thrown up. It seemed

clear that the natives would not have got in and out of the cave in this fashion, and eventually I succeeded in locating an entrance to the cave on top of the cliff. The natives have marked this entrance with a white representation of a snake, drawn as though emerging from the opening. The entrance is a narrow solution pipe which descends almost vertically for 30 feet.

The *Nurunguni* figures in the cave are large men, painted in red ochre, the tallest standing 4 feet high (Plate V, Fig. 1). Two have the long ears of "lightning men," while another is shown upside-down. A similar painting I was shown in Gidya country was said to be frog *Nurunguni* "going down for water."

I met only one native who knew this cave, and he could not tell me anything regarding the significance of the paintings. Like other Bunaba people he did not regard the *Nurunguni* as paintings, but said that they had left themselves in the cave during the "long time" dreamtime. He thought that the cave was named *Bunjadi*.

I have been told by Aborigines of other important cave galleries in Bunaba country, located near Lily Hole Spring on Leopold Downs Station, and behind the abandoned Oscar Range homestead. Each of these galleries is said to feature a large *Nurunguni-Nowungoo*.

Kuniandi Tribe

The tribal country occupied by the Kuniandi embraced the country east of the Fitzroy River on Gogo, Fossil Downs, Louisa Downs, and Margaret River Stations. Much of this country is occupied by limestone ranges, with many caves, and several galleries are said to be present in this area. The only one that I have studied in any detail is at Menyous Gap, 20 miles south-east of Fitzroy Crossing (map locality 8). The natives tell me that this is the best of the galleries in Kuniandi territory. I briefly saw other paintings at Mountain Home Spring, in the Home Range.

Menyous Gap.—Menyous Gap is a dry pass through the Pillara Range, on Gogo (Margaret Downs) Station. The cave with paintings is situated on the eastern wall of the gap, near the southern entrance. Menyous Gap is known to the natives as Youalon, but there does not seem to be a special name for the cave. The general name for cave used by the Kuniandi is *Duu*, or sometimes *Najee*, a name which comes from the Wolmadjari language.

The cave is decorated with many paintings in charcoal, white clay, and red ochre (Plate V, Fig. 2). The Kuniandi use the same name for the paintings as the Bunaba, that is *Nurunguni*. They also believe that the *Nurunguni* are people and animals who wandered the earth during the far-off dreamtime and left their images in the caves. The main figure in the cave at Menyous Gap is *Nurunguni-Gnarboo*, the All-Father. *Gnarboo* is also the name used for a person's natural father, corresponding to *Nowungoo* of the Bunaba. *Nurunguni-Gnarboo* is regarded as the creator who made all the features of the landscape, together with the grass, trees, etc. The animals shown in the cave accom-

panied him, and were the first representatives of their particular species. The Kuniandi believed that the *Nurunguni-Gnarboo* brings the rain, and until relatively recently the painting used to be touched up towards the close of each dry season to ensure the normal arrival of the "wet." The *Nurunguni-Gnarboo* painting in Menyous Gap is 9 feet 6 inches long. He is drawn in red ochre, white clay, and charcoal. His unusual horseshoe-shaped head is said to represent the rainbow, and he differs from other *Wandjina*-type paintings in having a mouth, and having three cicatrices across his chest. Above the head is a large arm painted in red ochre, and I was told that this was also the arm of the All-Father, pointing towards his own image, indicating "this is me." Above and across this arm is a human figure in white clay with a tall paper-bark headdress. This is said to be *Nurunguni-Junba*, who first introduced the Junba Corroboree in the "long-time" dreamtime. Above him is a crocodile (*lalanggarra*), and a kangaroo (*djeroo*). Astride the kangaroo is a spirit child (*jinganyara*), and beside it are clouds (*urrieroo*) with falling rain (*beedi*). There are also several representations of turtle (*junggur*) and emus (*kulnagnanja*), a single boomerang (*kylie*) and the rainbow serpent (*Galeru*).

Gidya Tribe

During the course of my geological work in the Kimberleys I have had little contact with the Gidya Tribe, as their territory lies outside the sedimentary basin where Wapet is prospecting for oil. However I made one quick geological trip to Bedford Downs Station, which is in Gidya country, and was shown a gallery about 2 miles west-north-west of Elgie Cliffs homestead (map locality 9) by a native named Clifton (*Jengarrie*). The gallery is in a large cave situated high in a cliff face near a permanent spring, in a district known to the natives as *Kulowali*. This locality is close to the boundary between the West, East, and North Kimberley Regions.

The main feature of the paintings (Plate VI, Fig. 1), which are referred to as *Nurunguni*, is a series of snakes, probably representing the rainbow serpent, though I was not able to confirm this. There are also frogs, some of which were said to be "going down for water," birds, wallabies, stencilled hands, and a representation of the sun.

Owing to the small amount of time I spent in Gidya country I was not able to learn much regarding the significance of the paintings to the natives. However it appears that the Gidya, like the Bunaba, do not connect the *Nurunguni* with rain-making, and they do not believe that the paintings were put there by Aborigines. The Gidya and Bunaba languages are very similar, and their mythological beliefs may also correspond rather closely.

Nyigina Tribe

The territory occupied by the Nyigina Tribe followed the Fitzroy River from Derby to near Fitzroy Crossing. I have seen only one gallery

in Nyigina country, and this is situated on the west side of Mt. Anderson, $2\frac{1}{2}$ miles north-west of the homestead (map locality 10).

The gallery is located in a sandstone rock shelter, and is characterized by the presence of numerous stencilled hands. Some stone-axe stencils are also present, and I have not seen these in any of the other galleries of the West Kimberley. There are also several paintings of human figures, the most striking being that of a man with his arms in the air. I was told that he was *Eballa* or *Uloo*, the All-Father, but obtained conflicting reports as to whether he and the other figures were drawn by natives. One old man told me that *Bugarara* (dreamtime) made the paintings, but another said that it was always known that the paintings were the work of natives, and they were nothing to do with *Bugarara*. The latter informant said that the most important function of the paintings, and of the stencillings in particular, was to serve as mementoes of the persons who made them. After a man died a painting or hand stencilling made by him would be viewed reverently by his near relatives, and would serve to remind them of him for many years.

The gallery also contains paintings of the rainbow serpent, a few animals, and various symbolic paintings in concentric and radiating designs. The radiating designs are said to represent the routes of the various ancestors of the tribe in reaching Mt. Anderson. All the paintings are referred to as *Womba*.

A few paintings, now very much eroded, are present in a large cave with a permanent spring of fresh water, located about $\frac{1}{4}$ -mile from the rock shelter. I was unable to determine a name for the rock shelter or the cave, but the natives refer to Mt. Anderson itself as *Djarmadangabu*.

Mangala Tribe

The Mangala is one of the desert tribes, which occupied the area around the Edgar Ranges, south of the Fitzroy River. I have only seen one example of the rock art of these people; it is situated in a sandstone cave about $\frac{1}{2}$ -mile south-west of the abandoned Dampier Downs homestead (map locality 11).

The paintings in this cave (Plate VI, Fig. 2) have been drawn in charcoal and white clay and are of a radically different type from the others described in this paper. They feature zigzag and hooked designs, and one conventionalized human figure, quite different from the rock paintings of the area north of the Fitzroy River. Designs of this type are a feature of the sacred boards (*koonarri*, *yiring yiring mandagi*, *pullawonoo*) and weapons of the southern Kimberley tribes, and they symbolize the paths taken by the All-Father during his journeyings in the long-past dreamtime. Mangala men know that the paintings were drawn by natives, though it appears that the women may be told of a supernatural origin for them.

I have not seen any rock paintings in the country occupied by the Karadjeri, Wolmadjari, and Djaru, other desert tribes bordering on the West Kimberley Region. However I was told that there is a good gallery in Wolmadjari territory, in the Poole Range. There are relatively few good caves in the desert country, and the artistic instincts of the men of these tribes are mainly directed towards the carving of their sacred boards, which are often beautifully decorated with intricate designs.

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15.—Glaciated Pavement in the Ripon Hills, Western Australia*

By D. J. Forman†

Manuscript received—21st June, 1960

Introduction

During 1958 a combined party from the Bureau of Mineral Resources and Geological Survey of Western Australia mapped manganese deposits in the Ripon Hills (see Fig. 1). During this mapping a glacial pavement was discovered. Good outcrop of rock makes it possible to reconstruct the history of the glaciation and the later events.

Glacial deposits of late Palaeozoic age are known in Western Australia from the Collie Basin, Irwin River Basin, Carnarvon Basin, Lake Carnegie-Wilkinson Range area, Bonaparte Gulf Basin, Fitzroy Basin, and the south-west part of the Canning Basin.

Glacial pavements are known to outcrop on the edge of the Carnarvon Basin in Nyarra Creek on the west side of the Carrandibby Range and at a locality about 4 miles east of Coordewandy Homestead (Konecki, Dickins and Quinlan 1958, p. 17). In addition a number of glacial pavements are known in the Pilbara District between the Nullagine and Oakover Rivers. J. N. Casey has allowed the author to examine an unpublished paper (Traves and Casey, unpublished paper) in which two of these pavements are described: one two miles north of Carawine Gorge and the other 14 miles to the south-east (Casey and Wells 1956). The present paper describes a third glaciated pavement from this area which differs from those described by Traves and Casey in that it is not considered to be a roche moutonnée.

Geology of the Pavement Area and Description of the Pavement

The glacial moraine at Ripon Hills is correlated with the Braeside Tillite and the Paterson Range Formation. Neither of these formations is known to be fossiliferous and it is only known for certain that the glacials were deposited between Upper Proterozoic and Upper Triassic or Jurassic times. Traves and Casey consider that the Braeside Tillite is probably of the same age as the Grant Formation of the Fitzroy Basin and the Lyons Group of the Carnarvon Basin and hence assign a tentative Lower Permian age to it.

The pavement is carved into chert breccia of probable Upper Proterozoic age (see Fig. 1). The chert breccia is folded into a number of closely spaced amoeboid domes and basins which are reflected in the present topography: the folding is probably the result of faulting.

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Examination of aerial photographs shows a strong northerly-trending lineament, on the east side of which the breccia has been uplifted to form a strong range of hills. To the west the relief is rugged but the hills are generally lower.

The pavement lies at the base and at the northern edge of the eastern range of hills. It is mound-shaped (see Plate I, Fig. 1) and elongated in the direction of ice movement, and has a polished surface exhibiting striations, grooves, chatter marks, and pitting due to ice plucking (see Plate I, Fig. 2). These features show that ice movement was in the direction 335° and indicate that the glacier descended from the range of hills to the immediate south.

To the west and north the pavement is overlain by tillite and fluvioglacial sandstone. The tillite contains boulders up to 2 feet in diameter, dominantly of sandstone, basalt, chert, and chert breccia. The glacial sediments are draped over the pavement and probably extend north-north-west under the Tertiary cover. The moraine is interpreted as terminal moraine.

(?) Tertiary sediments form a lake deposit. The lake formed after the glaciation and its sediments abut against the glacial moraine. Similar deposits occur further east, where they appear to grade into the Oakover Beds.

Throughout the Ripon Hills erratics are common. The erratics occur on the tops of hills and in valleys. One boulder of granite presents clear evidence that it was derived from beyond the present limits of the Ripon Hills.

Conclusion

A glacial pavement occurs at Ripon Hills. It lies at the base of a range of hills from which the glacier descended. On reaching the valley below, the ice melted, dumped its load, and formed contemporaneous fluvioglacial deposits, which protected the pavement from erosion. Later, in (?) Tertiary times, a lake formed north of the glacial deposits. Detritus deposited in the lake is now found dipping off the glacial moraine and has assisted in protecting the pavement and associated glacial deposits from subsequent erosion.

References

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1



2

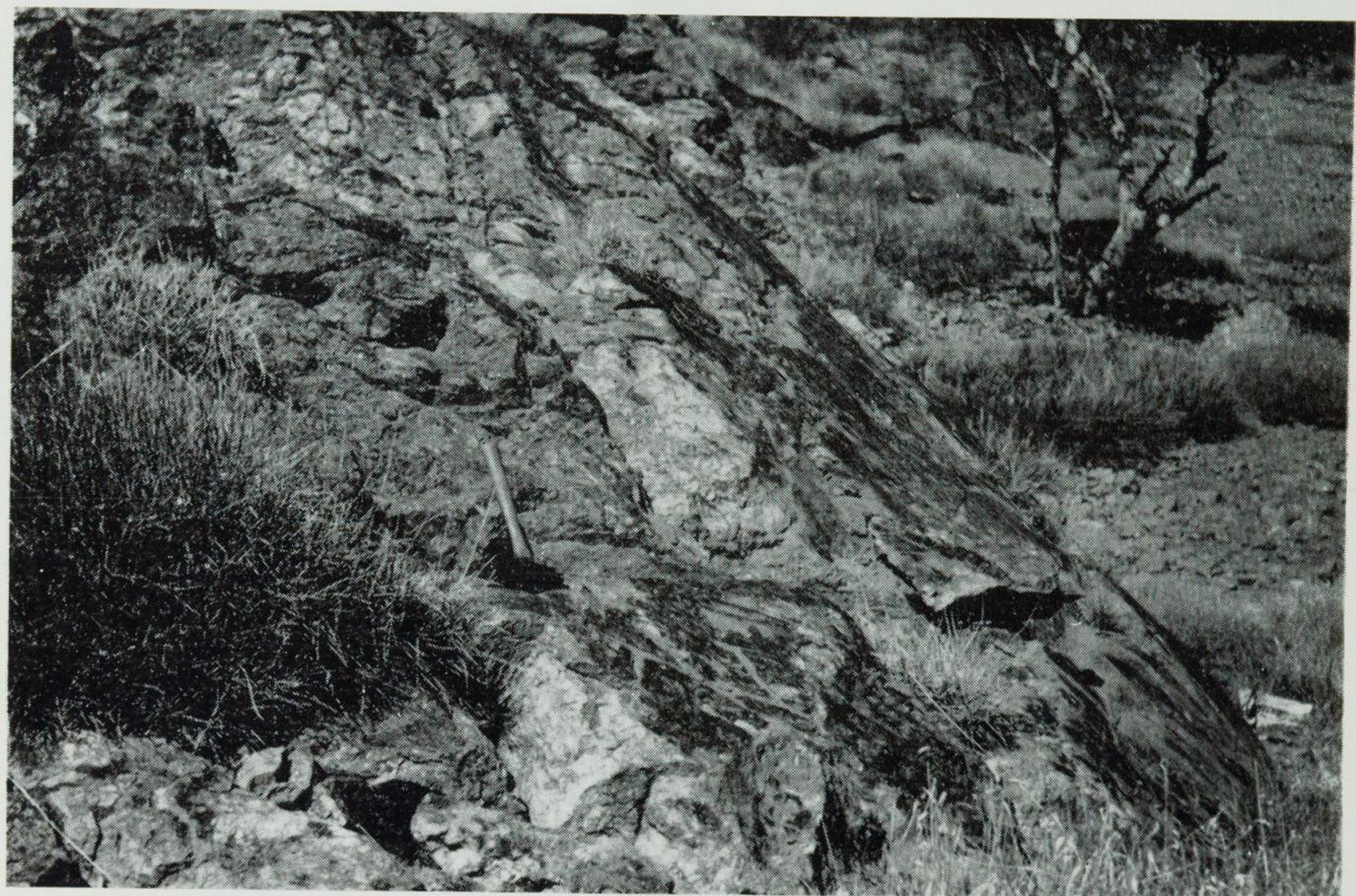


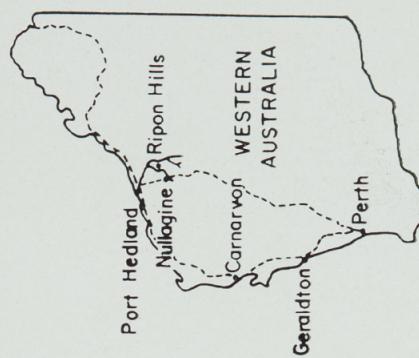
PLATE I

Fig. 1.—Glaciated pavement in the Ripon Hills. View, looking slightly west of north, showing: pavement in foreground, glacial sediments in west cliff face and lake sediments in east cliff face. Both breakaway scarps may be seen.
Fig. 2.—Glaciated pavement in Ripon Hills. View looking south-east showing polished undulating surface of chert breccia on west side of pavement.

Correlated
with
Lithology

| | | |
|-------------------|--|---|
| QUATERNARY | $\overbrace{\quad}$ Qs $\overbrace{\quad}$ | Rubble, Soil, alluvium |
| ? TERTIARY | $\overbrace{\quad}$ T $\overbrace{\quad}$ | Conglomerate, poorly sorted angular sandy siltstone |
| PERMIAN | Tillite and Tillite | Tillite and fluvio-glacial sandstone |
| UNCONFORMITY | Pu | Silicified siltstone and conglomerate |
| UNCONFORMITY | Pus | Manganiferous and ferruginous siltstone |
| UNCONFORMITY | Pub | Chert breccia and ripple marked sandstone |
| UPPER PROTEROZOIC | | |

LOCALITY MAP



→ Direction of glacial strike
← Stream
— Breakaway
— Contour height assumed
— 1000' Contour height assumed

GEOLOGICAL MAP
SHOWING
PAVEMENT RIPON HILLS WA.

